Searches for Physics beyond the Standard Model from HERA

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Abstract. Searches for physics beyond the Standard Model are reported from electron-proton collisions at a center of mass energy of 318 GeV. Results on a completely model independent search for deviations from Standard Model predictions at large transverse momenta are reported as well as generic searches for contact interactions, leptoquarks and excited fermions from the H1 and ZEUS experiments.

PACS. 14.80.-j Other particles (including hypothetical)

1 Electron-Proton Data from HERA

The HERA collider at DESY has provided since 1992 electron-proton data at centre-of-mass (CMS) energies a factor 15 larger than at previous fixed target experiments, and provides the highest CMS energy for collisions with a lepton in the initial state. The HERA II run, which ended in June 2007, has delivered both electron and positron beams with left and right handed polarisation of 40% on average. The total integrated luminosity used per experiment is close to 0.5 fb^{-1}, an increase by about a factor of four with respect to the HERA I run alone. First preliminary analyses of the H1 and ZEUS experiments making use in most cases of all these final data sets will be presented in the following. Typical trigger thresholds of 5 to 10 GeV for electrons and jets have lead to about 10^8 triggered events. Systematic errors of measurements are most often dominated by the 1 - 3 % uncertainty of calorimeter energy scales as obtained from kinematic constraints. Luminosity and polarisation are measured with 1.6 - 3 % and 3 - 5% uncertainty, respectively.

Recent HERA results on Standard Model (SM) processes include Neutral and Charged Current cross sections ranging up to Bjorken-x values of 0.65. The large CMS energy implies measurements of momentum transfer Q^2 up to 30000 GeV^2, i.e. far beyond $M^2_{W,Z}$, where the helicity structure of weak interactions is probed for all four combinations of electron charge and polarisation, $e^{\pm}_{L,R}$. Using inclusive as well as jet data at large transverse momenta has provided the worlds most precise determinations of parton density functions and, in a recent combination of H1 and ZEUS data, a determination of the strong coupling constant from jets of $\alpha_s(M_Z) = 0.1198 \pm 0.0019(exp.) \pm 0.0026(th.)$, where the theory error is dominated by the scale uncertainty of the NLO calculation.

2 Model- independent Search

In comparison to direct searches for specific signatures predicted by models beyond the SM, generic, model-independent searches have both advantages and disadvantages. In model independent searches

- many final states are investigated simultaneously leading to a rather complete view on agreement or disagreement with SM predictions;
- the phase space for each channel cannot be restricted very much in order not to bias the selection to specific assumptions on the final state kinematics. Unfortunately this also implies that the separation power between a possible signal and SM background is significantly reduced;
- even if no deviation from SM predictions is found it is not possible to argue that new physics cannot be found in the same data, because of the reduced separation power;
- any disagreement with respect to SM predictions is difficult to quantify, because the likelihood for single, large deviations is sizeable once many distributions with many possible regions of interest have been looked at.

In a recent analysis [1] the H1 collaboration has presented a solution to this last item. Using all HERA II data, final states with any number of electrons, muons, photons and hadronic jets with transverse momentum $P_T > 20$ GeV as well as possible missing transverse momentum $P_T^{miss} > 20$ GeV have been investigated. The resulting event classes have been analysed with respect to invariant mass M of the hard process and transverse scalar momentum $P_T = \sum |P_{T,i}|$, as motivated by possible new resonances or Jacobian peaks. For each channel all possible kinematic ranges of M and P_T have been considered to find the one with the most significant deviation from SM predictions. Examples for the P_T distributions of all event classes with data are shown in Figure 1. For the processes with

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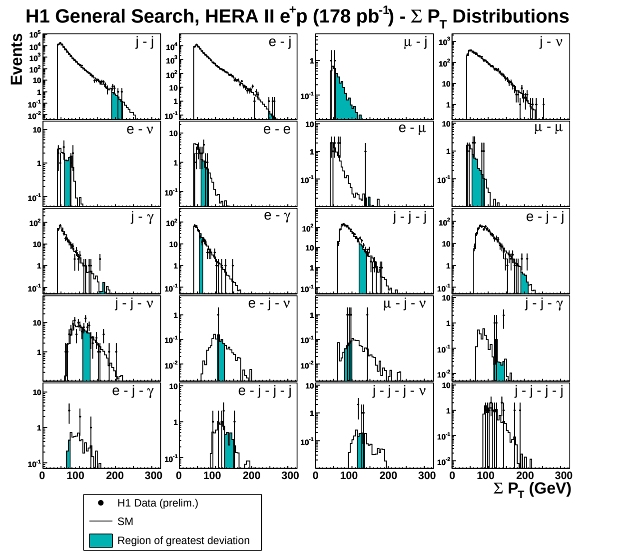

Fig. 1. Transverse momentum distributions for the event classes of the H1 model independent search [1] for e^+p data. The shaded areas denote the regions of maximum deviation from SM predictions.

the largest cross sections, i.e. ej, νj, jj, where j denotes jet and ν denotes P_T^{miss}, transverse momenta up to 250 GeV are reached. For large multiplicity classes the number of events is very small, as expected. The agreement with SM expectations is generally convincing. To quantify this, all possible combinations of lower and upper cuts on the quantity shown are applied in order to select the region with largest statistical difference with respect to expectation for each event class (shaded areas). Taking into account experimental and theoretical errors for both data and prediction for each event class, the probability $\hat{P}$ for observing a maximum deviation larger than the one in the data has been determined from a large number of Monte Carlo experiments, which are based on the SM prediction. Figure 2 shows the distribution of these probabilities for all event classes. The distribution of probabilities $\hat{P}$ for large fluctuations in the data closely follows the expectation of the Monte Carlo experiments, indicating that overall the data set as well as the statistical procedures are well understood. For the 88 distributions looked at, the largest deviation in the data has a probability of about 2% ($-\log_{10} \hat{P} = 1.7$). It corresponds to final states with a muon, a jet and missing transverse momentum. A more detailed study of this event class is presented in [2]. Note that this deviation is not observed by the ZEUS experiment in a comparable analysis [3].

3 Contact Interactions

Extensions of the SM often involve new particles with masses beyond the kinematic reach of current colliders, which nevertheless imply new interactions between the known fermions. In this case the 4-momentum transfer

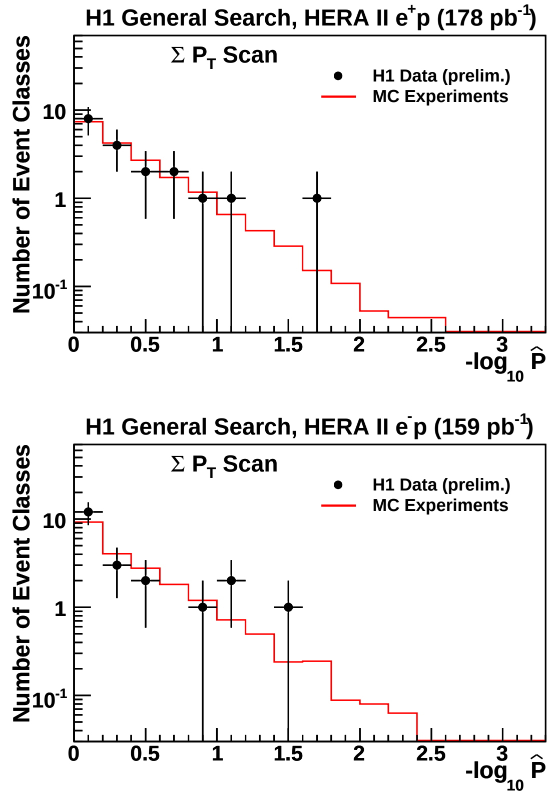

Fig. 2. Probability of the maximum deviation within the P_T distribution of all event classes, for e^+p (top) and e^-p (bottom) data from H1 [1].

Q^2 is smaller than the mass of the new particle, so that the propagator can be approximated by a constant. In this "contact interaction" limit, many types of new interactions can thus be parameterised by a pure 4-fermion interaction of the form (for ep scattering at HERA)

$$L_{CI} = \sum_{i,j=L,R;q=u,..b} \eta_{ij}^q \, J_{e,i}^\mu \, J_{\mu\, q,j}$$

where e.g. $J_{e,L}^\mu = \bar{e}_L \gamma^\mu e_L$ denotes the common left-handed electron current. While historically contact interactions have been discussed mostly in the context of new gauge bosons, compositeness models and fermion radius, it was recently also used to constrain large extra dimensions and even unparticle physics [4]. In any of these cases the constants η_{ij}^q have to be chosen appropriately to reflect the scale and the helicity structure of the new interaction.

At HERA, the high precision data on inclusive deep inelastic scattering, $ep \to eX$, as a function of Q^2 have been used to constrain contact interactions. Here an analysis [5] by the ZEUS collaboration is presented which is based on an integrated luminosity of 274 pb^{-1}. The data exhibits the sharp decrease as a function of Q^2 expected due to the approximate $1/Q^4$ dependence of the propagator for γ/Z interference folded with the steeply falling quark distributions at large x. Shown in Figure 3 is the ratio of the data and the SM prediction

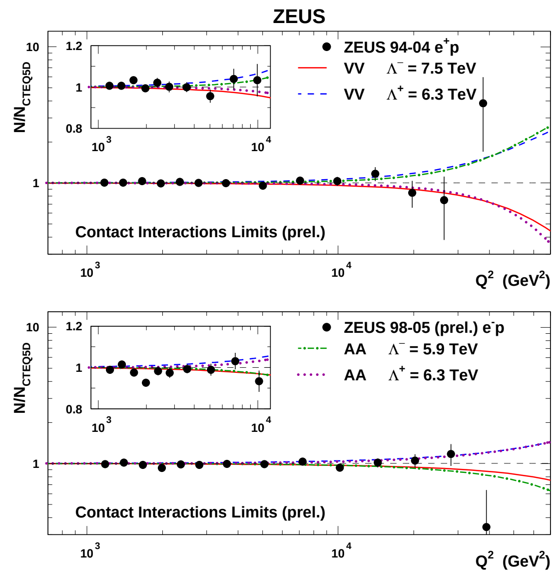

Fig. 3. Ratio of inclusive neutral current deep inelastic scattering data and SM expectation as a function of Q^2, for e^+p (top) and e^-p (bottom) data from ZEUS [5]. Also shown are predictions based on contact interactions with pure vector (VV) and pure axial-vector (AA) currents. The scales $\Lambda^\pm$ chosen here for positive (+) or negative (−) interference correspond to the limits (95% C.L.) obtained by comparing these predictions with the data shown.

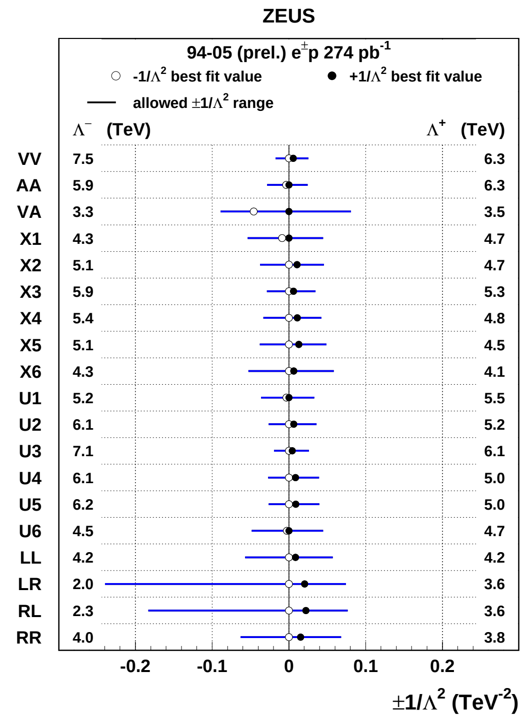

Fig. 4. Confidence intervals of $\pm 1/\Lambda^2$ for general contact interaction scenarios. The numbers at the right (left) margin are the corresponding lower limits on the mass scale Λ^+ (Λ^-). The filled (open) circles indicate the positions corresponding to the best-fit coupling values, for positive (negative) couplings [5].

which is based on a NLO QCD fit to inclusive DIS data from ZEUS and from fixed target experiments. Note that the prediction used here, in the region of interest at high Q^2, is dominated by the precision of fixed target experiments, which have measured at large x but much smaller Q^2, and of the α_s dependent QCD evolution of parton densities towards large Q^2. Therefore the bias of using ZEUS for both data and SM prediction is small.

Within errors, the data show no significant deviation with respect to the SM expectation. Taking into account experimental statistical and systematic uncertainties as well as the error on α_s and on the parton densities, fits to the strength of various models leading to contact interactions have been performed.

- Model independent results on contact interactions, depending only on the helicity structure, have been determined. In the strong coupling limit $\eta = 4\pi/\Lambda^2$, scales Λ in the range of 2 TeV to 7.5 TeV can be excluded (Figure 4).
- Leptoquarks (LQ) with masses M_{LQ} above the CMS energy of HERA (318 GeV) might contribute to the inclusive ep cross section via virtual exchange. At high M_{LQ}, the propagator for LQ exchange will contract to a form $\eta \sim \lambda^2/M_{LQ}^2$, where the coupling λ refers to the $e-q-LQ$ vertex. Considering all possible quantum numbers for leptoquarks compatible with the gauge symmetries of the SM as well as lepton and baryon number conservation, limits on M_{LQ}/λ in the range 0.3 TeV to 1.9 TeV are derived. For masses below 318 GeV these bounds are complemented by direct searches for LQ decays, which lead to bounds on λ much smaller than 10^{-2}.
- Squarks in R-parity violating Supersymmetry with a $\lambda'_{ijk} L_i Q_j D_k$ type interaction are constrained (simular to leptoquarks) to $M_{LQ}/\lambda' > 0.44$ TeV.
- Large extra dimensions also lead to deviations from SM predictions and can thus be constrained to scales $M_S > 0.88$ TeV.
- A finite radius R_q of quarks leads to a form factor which changes the cross section by a factor $(1 - R_q^2 Q^2/6)^2$. The quark radius can thus be constrained to $R_q < 6.7 \times 10^{-19}$m.

4 Search for excited leptons

In models of composite fermions, excited states are to be expected which can be produced in processes with large momentum transfer. For experimental investigations the LEP and HERA experiments have employed the most general model with spin 1/2, isospin 1/2, left and right handed symmetric doublets of excited fermions. The corresponding term in the lagrangian for the tensor coupling between a SM lepton doublet, an excited lepton and the SM gauge bosons is

$$L_{L^*L} = \frac{1}{2\Lambda} \bar{L}_R^* \sigma^{\mu\nu} \left[g f \frac{\boldsymbol{\tau}}{2} \partial_\mu \boldsymbol{W}_\nu + g' f' \frac{Y}{2} \partial_\mu B_\nu \right] L_L + h.c.$$

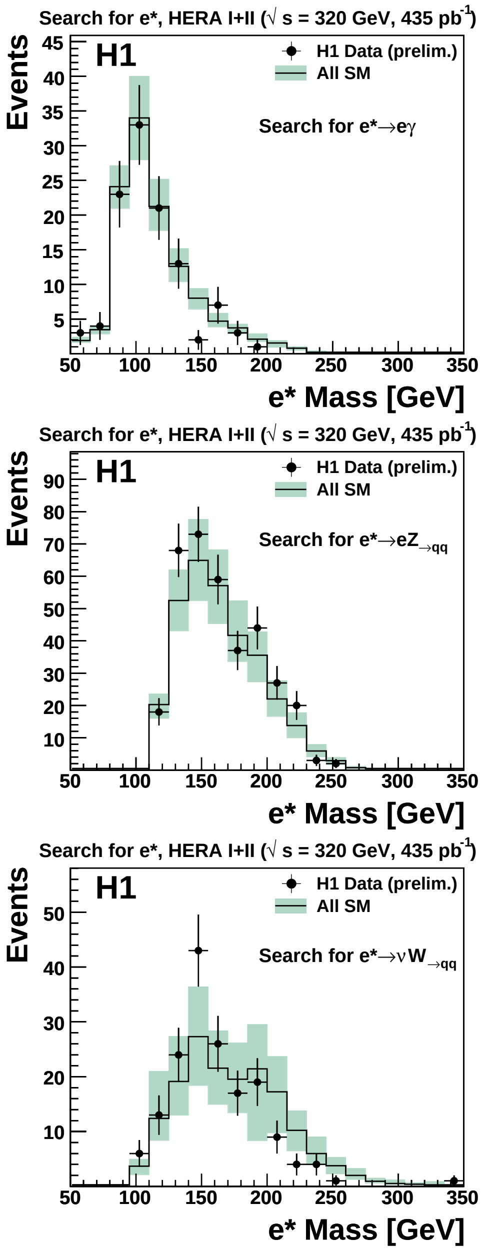

Fig. 5. Mass distributions of e^* candidates in final states with $\gamma, Z \to q\bar{q}$ or $W \to q\bar{q}'$ from H1 [6].

Here L_R^* denotes a righthanded doublet of excited leptons, $\sigma^{\mu\nu} = i/2\,(\gamma^\mu\gamma^\nu - \gamma^\nu\gamma^\mu)$, g and g' are the SM gauge couplings and Λ denotes the compositeness scale. The factor f thus describes the strength of the $SU(2)$ vertex $\nu^* e W^\pm$ relative to the $\nu e W^\pm$ vertex of the SM, and similarly f' for $U(1)_Y$ vertices.

Based on all their data taken at the largest HERA CMS energy of 318 GeV, the H1 collaboration has presented a preliminary analysis [6] for the decay modes $e^* \to e\gamma$, $e^* \to eZ$ and $e^* \to \nu W$ with W, Z decaying hadronically. Figure 5 shows the corresponding reconstructed masses of e^* candidates in the three decay modes. As no significant excess above the SM expectation is observed, limits as a function of mass and coupling f/Λ (for $f = f^*$) are derived (Figure 6). To

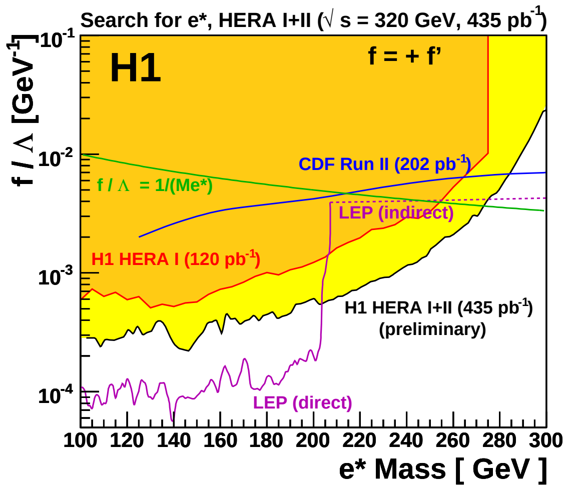

Fig. 6. Limits of excited electrons from LEP, Tevatron and H1[6].

give an example, e^* masses below 260 GeV, i.e. far beyond the kinematic reach of LEP, are excluded for Λ=1 TeV and f=2.

5 Conclusion

The H1 and ZEUS experiments have searched for deviations from Standard Model predictions, both in a completely model-independent way by looking in basically all final states, and in a partially model independent way by invoking the most general form of effective lagrangians for contact interactions, leptoquarks, large extra dimensions and compositeness (quark radius and excited leptons). In preliminary analyses using in most cases all their high energy data until the end of the HERA running in June 2007, no significant deviations have been found and constraints on the corresponding couplings are derived for masses reaching typically up to 280 GeV. It is a remarkable success that, at the large scales of interest here, all the many final state measurements at HERA are correctly described by Standard Model predictions.

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