

## EXOTIC PHYSICS AT HERA

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A search for excited neutrinos, the analysis of multi-lepton final states, a search for doubly charged Higgs production and a general search for high- $P_T$  phenomena at HERA are reported. The searches use data samples of  $e^\pm p$  collisions with a centre-of-mass energy  $\sqrt{s} = 320$  GeV collected by the H1 and ZEUS experiments at HERA in the years 1994-2005 with integrated luminosities up to  $\mathcal{L} = 296$  pb $^{-1}$ . Overall no significant deviations of the experimental observations from the Standard Model (SM) expectation are found.

*Keywords:* Search; Leptons; Neutrino; Compositeness; Higgs; BSM.

### 1. Introduction

HERA is a collider on the energy frontier providing  $ep$  collisions at a centre-of-mass energy  $\sqrt{s} = 320$  GeV. It can explore parts of the phase space not reachable by other colliders, opening a unique window for the search for new physics. A classic search for physics beyond the Standard Model (BSM) is the search for compositeness of elementary particles. Section 2 presents a search for excited neutrinos. It profits from the tenfold increase in statistics of the  $e^-p$  data sample collected in HERA-II (2003-05,  $\mathcal{L} \simeq 180$  pb $^{-1}$ ) with respect to HERA-I (94-00,  $\mathcal{L} \simeq 20$  pb $^{-1}$ ). This  $e^-p$  data sample is also searched for events with multiple leptons in the final state (Section 3). Pairproduction of  $\tau$ -leptons is measured for the first time at HERA. Of particular interest was the high mass and  $P_T$  region in light of the excess of  $ee$  and  $eee$  events observed in the HERA-I sample. The significance of the excess does not increase using the full sample. The interpretation of these events in terms of doubly charged Higgs  $H^{\pm\pm}$  production is performed in a dedicated search (Section 4).  $H^{\pm\pm}$  production is ruled out for the  $ee$ -case. Also a general, model-independent search for high- $P_T$  phenomena is performed on the HERA-II  $e^-p$  data sam-

ple looking for deviations from the SM in a multitude of final states with high- $P_T$  objects (Section 5).

### 2. Search for Excited Neutrinos

Compositeness of fermions provides a natural solution for the fermion mass hierarchy problem in the SM<sup>1</sup>. The excitation part of a Lagrangian for a minimal extension of the SM to allow excited fermions considering only electroweak interactions can be written

$$L_{F^*F} = \frac{1}{2\Lambda} \overline{F_R^*} \sigma^{\mu\nu} [gf \frac{\vec{\tau}}{2} \partial_\mu \overline{W}_\nu +$$

$$g' f' \frac{Y}{2} \partial_\mu B_\nu] F_L + \text{h.c.},$$

where the weights  $f$  and  $f'$  modify the electroweak  $SU(2) \times U(1)$  couplings  $g$  and  $g'$ , respectively.  $W$  and  $B$  denote the gauge boson fields,  $\sigma_{\mu\nu}$  the Pauli matrices and  $Y$  the weak hypercharge. Compositeness comes into the play at the scale  $\Lambda$  and the weights  $f$  and  $f'$  determine the production cross section and decay branching ratios of excited fermions. The cross section for excited neutrino production is about 80 times larger in  $e^-p$  than in  $e^+p$  for high  $M_{\nu^*}$  due to the  $W$  exchange involved.

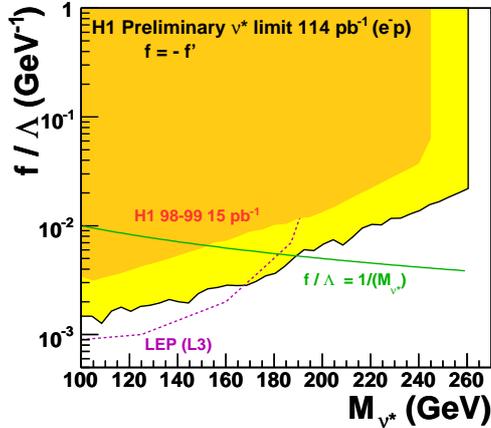


Fig. 1. Limits on the ratio  $f/\Lambda$  for the assumption  $f = -f'$  (maximal coupling  $\gamma\nu\nu^*$ ).

Investigated final states are  $\nu^* \rightarrow \nu\gamma$ ,  $\nu^* \rightarrow \nu Z \leftrightarrow q\bar{q}$  and  $\nu^* \rightarrow eW \leftrightarrow q\bar{q}$ . No signal of  $\nu^*$  production was found<sup>2</sup>. Limits on the cross section in the plane of the ratio  $f/\Lambda$  and the mass of the  $\nu^*$ ,  $M_{\nu^*}$  are presented in Fig. 1 for the hypothesis  $f = -f'$  corresponding to maximal  $\gamma\nu\nu^*$  coupling. Assuming  $f/\Lambda = 1/M_{\nu^*}$ , excited neutrinos with masses below 188 GeV are excluded at 95% CL. The results extend previous searches at HERA<sup>3</sup> and are sensitive beyond LEP reach.

### 3. Multi-Lepton Events

Within the SM framework multi-lepton events at high  $P_T$  are produced mainly via  $\gamma\text{-}\gamma$  interactions<sup>4</sup>.

An H1 preliminary analysis<sup>5</sup> using a data sample corresponding to 275  $\text{pb}^{-1}$  selects two central leptons (electrons and muons) with  $P_{T1,2} > 10, 5$  GeV. Leptons are counted and the events classified accordingly ( $ee, eee, \mu\mu, e\mu, e\mu\mu$ ). Additional electrons are allowed. In the  $ee$  sample at high invariant mass  $M_{ee} > 100$  GeV three events are selected where 0.44 are expected.

H1 published a measurement of production of  $\tau$ -leptons<sup>6</sup> using 118  $\text{pb}^{-1}$  of HERA-I data. Elastic  $\tau$ -pair decays with the final state combinations  $e\text{-}\mu$ ,  $e/\mu\text{-}jet$  ( $jet =$

hadronic  $\tau$ -decay) and  $jet\text{-}jet$  in the phase space  $P_{T\tau} > 2$  GeV and  $20^\circ < \theta_\tau < 120^\circ$  are analysed. In the final sample 30 events are observed for  $27.1 \pm 4.1$  expected from the SM with a  $\tau$ -pair contribution of  $> 50\%$ . The measured cross section of  $13.6 \pm 5.7$  pb is in good agreement with  $11.2 \pm 0.3$  pb expected from the SM.

A ZEUS preliminary analysis<sup>7</sup> selects multi-electron samples ( $ee, eee$ ) and pairs of  $\tau$ -leptons in a data sample corresponding to 296  $\text{pb}^{-1}$ . The selection of multi-electron events is similar to the one done by H1. Figure 2 shows the invariant mass  $M_{ee}$  in the  $ee$  sample. At  $M_{ee} > 100$  GeV one event is observed where 1.5 are expected from the SM. Also  $\tau$ -pair decays with a  $e\text{-}\mu$  final state were searched in elastic events. Three events are observed and  $2.0 \pm 0.8$  and expected with negligible background.

All multi-lepton samples in both experiments show good overall agreement with the SM prediction, while the events at high mass remain intriguing.

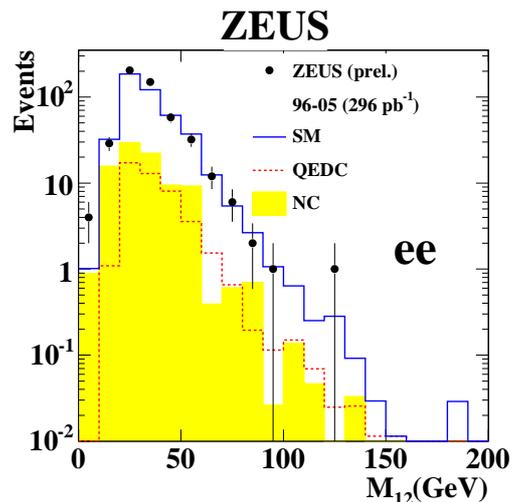


Fig. 2. Invariant mass of the two electrons in the di-electron sample observed by the ZEUS experiment.

#### 4. Search for Doubly Charged Higgs Boson

The excess of  $ee$  and  $eee$  events in HERA-I data at H1 has triggered a search for doubly charged Higgs bosons  $H^{\pm\pm}$ . These appear in various extensions of the SM, eg. left-right symmetric models<sup>8</sup>. A  $H^{\pm\pm}$  can be radiated off the incoming electron if there are non-vanishing Yukawa couplings  $h_{ee}$ ,  $h_{e\mu}$  or  $h_{e\tau}$ . The final state contains one electron and a lepton pair with the same charge as the incident electron. The present analysis<sup>9</sup> investigates  $H^{\pm\pm}$ -decays into  $ee$ ,  $e\mu$  and  $e\tau$  pairs using the unpolarised HERA-I data. The  $ee$  and  $e\mu$  channels are based on the selection presented in Sec. 3. The  $e\tau$  channel is investigated in  $\mathcal{L} = 88 \text{ pb}^{-1}$  of HERA-I data considering all possible decays of the  $\tau$  lepton ( $e$ ,  $\mu$  and hadronic) in the phase space  $P_T^{e,\tau} > 10, 5 \text{ GeV}$  and  $20^\circ < \theta_{e,\tau} < 140^\circ$ . In the final selection no excess over the SM expectation is observed. Figure 3 shows the upper limits on the Yukawa couplings  $h_{ee}$ ,  $h_{e\mu}$  and  $h_{e\tau}$  obtained by assuming that one coupling dominates. For dominating  $h_{e\mu}$ ,  $h_{e\tau}$  couplings H1 extends beyond the reach of searches from LEP<sup>10</sup> and TeVatron<sup>11</sup> (also shown). Assuming a coupling of electromagnetic strength  $h_{e\mu}(h_{e\tau}) = 0.3$ ,  $M_{H^{\pm\pm}} < 141(112) \text{ GeV}$  is excluded.

#### 5. General Search

The H1 collaboration has performed a general search for new high- $P_T$  phenomena by looking for deviations from the SM<sup>12</sup>. The HERA-II  $e^-p$  sample of  $159 \text{ pb}^{-1}$  is a complement to the published HERA-I  $ep$  sample ( $118 \text{ pb}^{-1}$ ) dominated by 87% of  $e^+p$  data<sup>13</sup>. The final states are classified by the number of identified electrons ( $e$ ), muons ( $\mu$ ), jets ( $j$ ), photons ( $\gamma$ ) and missing energy ( $\nu$ , eg. neutrinos). At least two such objects are required. They are identified in the phase space  $P_T > 20 \text{ GeV}$  and  $10^\circ < \theta < 140^\circ$  and have to be isolated. The results for HERA-II

are shown in Fig. 4. There are 22 channels with at least one observed or expected event. Also differential distributions of the invariant mass  $M_{\text{all}}$  of all objects in a class and the scalar sum of all transverse momenta  $\sum P_T$  were investigated by a statistical algorithm looking for deviations (excess or deficit) from the SM<sup>13</sup>. Good agreement with the SM is found in all channels.

#### 6. Conclusions

The recent HERA-II  $e^-p$  sample is a great complement to the mostly  $e^+p$  sample from HERA-I and provides a ten-fold increase in statistics of  $e^-p$  collisions. Stricter limits on excited neutrino production could be set and the reach extended to higher masses. This large  $e^-p$  sample is also used to perform a general search for deviations to the SM in a large variety of high  $P_T$  topologies. A good agreement with the predictions from the SM is observed in all channels.

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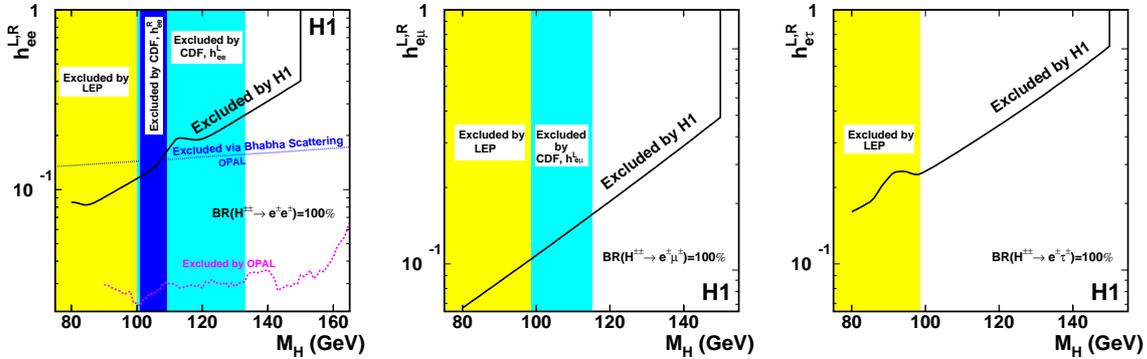


Fig. 3. Limits on doubly charged Higgs production assuming dominating couplings  $h_{ee}$  (left),  $h_{e\mu}$  (middle) or  $h_{e\tau}$  (right).

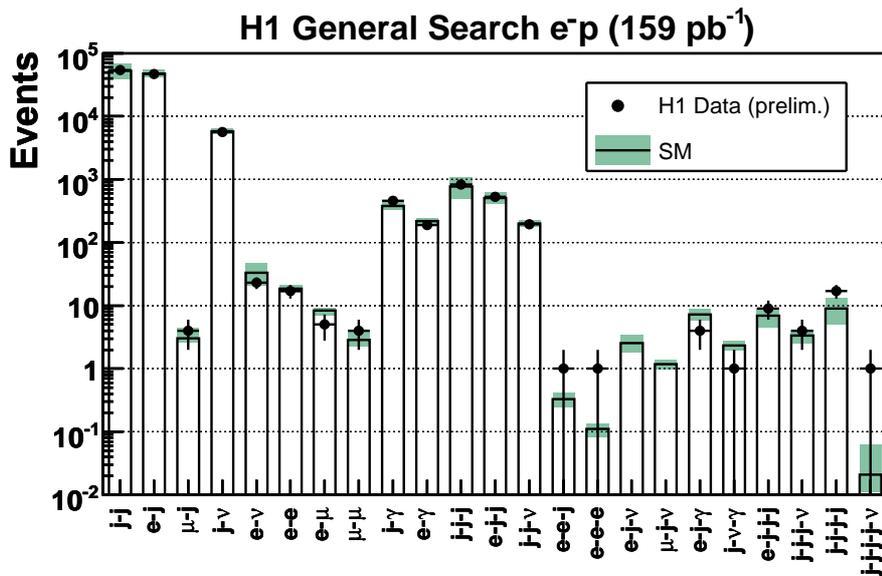


Fig. 4. HERA II  $e^-p$  event yields in the general search for new phenomena at high  $p_T$ . Data (points) are compared to the SM expectation (histogram bars). The uncertainty of the SM prediction is indicated by the shaded band.

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