SEARCHES FOR NEW PHYSICS IN ep COLLISIONS AT HERA

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Recent results from searches for physics beyond the Standard Model (SM) in $e^{\pm}$-proton collisions at HERA at center-of-mass energies of 300 and 320 GeV are presented. They were performed on a data sample collected in the period 1994 – 2004 by the H1 and ZEUS collaborations. The data have been analysed searching for leptoquarks, light gravitinos in R-parity violating supersymmetric models and magnetic monopoles. Results of a general search for new phenomena at high transverse momentum and of a dedicated search for events with isolated leptons and missing transverse momentum are also reported.

1 Introduction

At the HERA collider, electrons (positrons) and protons collide at a center-of-mass energy of about $\sqrt{s} = 320$ GeV (300 GeV before 1998). From 1994-2000 (HERA I), integrated luminosities of about $\mathcal{L} = 113$ pb^{-1} in e^+p and $\mathcal{L} = 17$ pb^{-1} in e^-p scattering were collected by each of the two experiments H1 and ZEUS. These data are used to search for new physics beyond the SM. Recent results on searches for leptoquarks [1] (section 2), for R-parity-violating ($\not{R}_p$) supersymmetry (SUSY) [2] (section 3) and magnetic monopoles [3] (section 4) are presented in this contribution.

A general search for new phenomena at high transverse momentum was recently performed in a model independent framework by the H1 collaboration using the 1994-2000 $e^{\pm}p$ data sample [4] and was repeated with the newest data taken after the HERA luminosity upgrade in 2003/2004 (HERA II) corresponding to $\mathcal{L} = 45\,\mathrm{pb}^{-1}$ ($\sqrt{s} = 320\,\mathrm{GeV}$) [5]. Results are presented in section 5.

The excess of events with isolated electrons or muons and missing transverse momentum ($\not{p}_T$) observed in the period 1994-2000 by the H1 collaboration [6,7] has motivated a repeat of the same analysis on the recent data taken in 2003/2004 corresponding to $\mathcal{L} = 53\,\mathrm{pb}^{-1}$ ($\sqrt{s} = 320\,\mathrm{GeV}$).

In section 6 the event yields are compared with results obtained by the ZEUS collaboration [8,9] performed on data taken from 1994-2000 ($\mathcal{L} = 130\,\mathrm{pb}^{-1}$).

2 Leptoquarks

The recent observations of neutrino oscillations have shown that lepton-flavor violation (LFV) does occur in the neutrino sector. The LFV induced in the charged-lepton sector due to neutrino oscillations cannot be measured at existing colliders due to the low expected rate. However, there are many extensions of the SM such as grand unified theories, SUSY, compositeness and technicolor that predict possible $e \to \mu$ or $e \to \tau$ transitions at detectable rates.

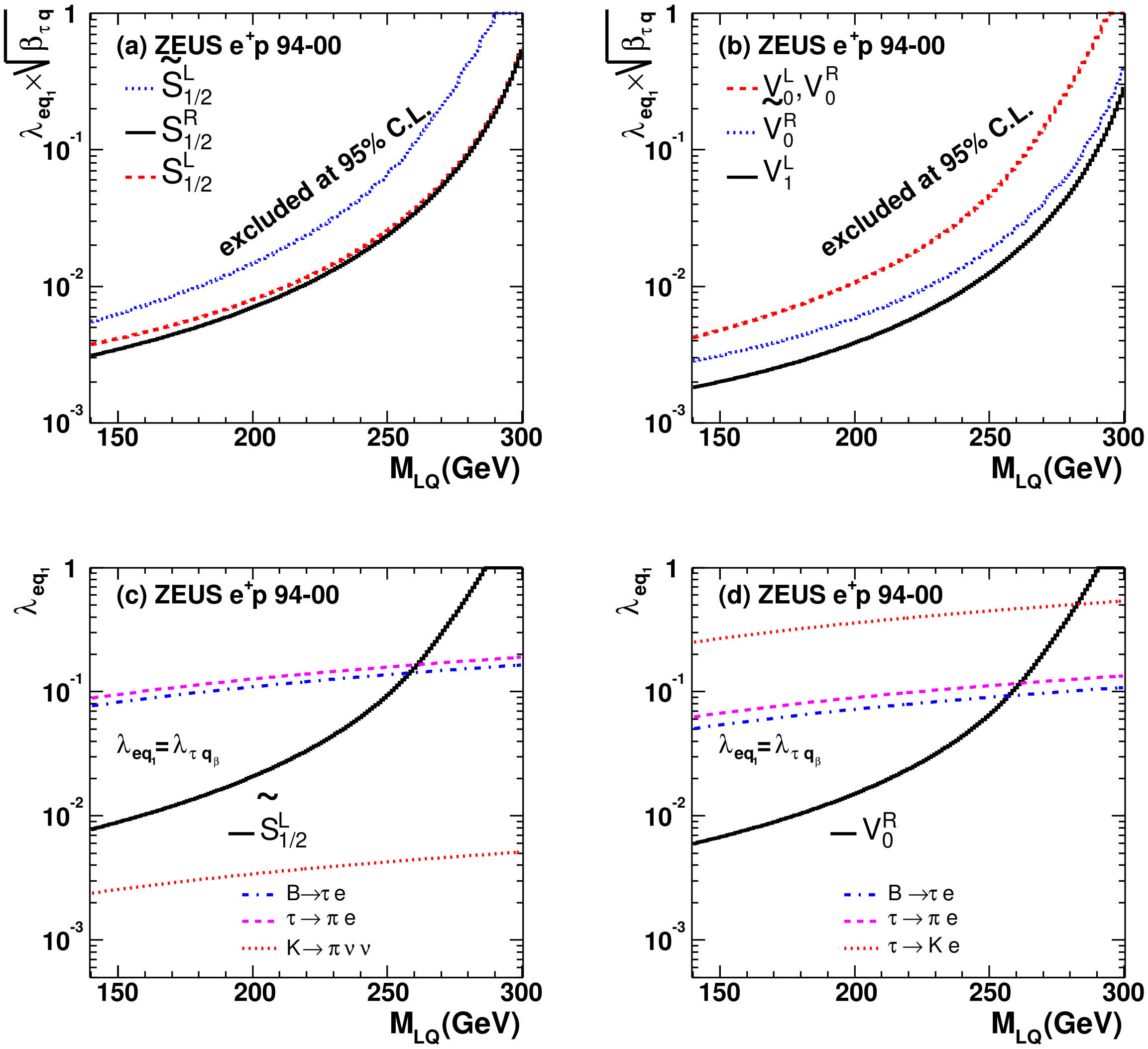

Figure 1: Limits for $F = 0$ LQs in the τ channel obtained from e^+p collisions. The upper plots show 95% CL limits on $\lambda_{eq_1} \times \sqrt{\beta_{\tau q}}$ for (a) scalar and (b) vector LQs. In the lower plots, ZEUS limits on λ_{eq_1} for a representative (c) scalar and (d) vector LQ are compared to the indirect constraints from low-energy experiments, assuming $\lambda_{eq_1} = \lambda_{\tau q}$.

A search for LFV interactions $ep \to \mu X$ and $ep \to \tau X$ has been performed with the ZEUS detector using the entire HERA I data sample [1]. The presence of such processes, which can be detected almost without background, would clearly be a signal of physics beyond the SM. No evidence for LFV was found and constraints were derived on LQs that could mediate such interactions. The Buchmüller-Rückl-Wyler (BRW) LQ model [10] is used to set limits from the search. LQs are bosons that carry both leptonic (L) and baryonic (B) numbers and have lepton-quark Yukawa couplings. Their fermionic number ($F = 3B + L$) can be $F = 0$ or $|F| = 2$. Such bosons arise naturally in unified theories that arrange quarks and leptons in common multiplets. A LQ that couples both to electrons and to higher-generation leptons would induce LFV in ep collisions through s- and u-channel processes.

For LQ masses below $\sqrt{s}$, limits at 95% confidence level (CL) as a function of the mass were set on $\lambda_{eq_1}\sqrt{\beta_{\ell q}}$, where λ_{eq_1} is the coupling of the LQ to an electron and a first-generation quark q_1, and $\beta_{\ell q}$ is the branching ratio of the LQ to the final-state lepton ℓ (μ or τ) and a quark q. For a coupling constant of electromagnetic strength ($\lambda_{eq_1} = \lambda_{\ell q} = 0.3$), mass limits between 257 and 299 GeV were set, depending on the LQ type. For $M_{LQ} = 250$ GeV, upper limits on $\lambda_{eq_1}\sqrt{\beta_{\mu q}}$ ($\lambda_{eq_1}\sqrt{\beta_{\tau q}}$) in the range $0.010 - 0.12 (0.013 - 0.15)$ were set. As an example, in the τ channel upper limits on $\lambda_{eq_1}\sqrt{\beta_{\tau q}}$ are shown in Fig. 1 for $F = 0$ scalar and vector LQs as a function of the LQ mass, assuming resonantly produced LQs as described by the BRW model. In Figs. 1 (c) and (d), the results are compared to constraints from rare τ, B or K decays [11]. ZEUS limits improve on low-energy results in most cases.

For LQ masses much larger than $\sqrt{s}$, limits were set on the four-fermion interaction term $\lambda_{eq_\alpha}\lambda_{\ell q_\beta}/M^2_{LQ}$ for LQs that couple to an electron and a quark q_α and to a lepton ℓ and a quark q_β, where α and β are quark generation indices. Some of the limits are also applicable to LFV processes mediated by squarks in $R\!\!\!/_p$ SUSY models. In some cases, especially when a higher-generation quark is involved and for the process $ep \to \tau X$, the ZEUS limits are the most stringent to date.

3 Light gravitinos in R-parity-violating SUSY

In Gauge Mediated Supersymmetry Breaking (GMSB) models, new "messenger" fields are introduced which couple to the source of supersymmetry breaking. The breaking is then transmitted to the SM fields and their superpartners by gauge interactions. The gravitino, $\tilde{G}$, is the lightest supersymmetric particle (LSP) and can be as light as 10^{-3} eV.

An investigation of $R\!\!\!/_p$ SUSY in a GMSB scenario was performed by the H1 collaboration for the first time at HERA [2]. R-parity is a discrete multiplicative symmetry which can be written as $R_p = (-1)^{3B+L+2S}$, where B denotes the baryon number, L the lepton number and S the spin of a particle. The most general supersymmetric theory that is renormalisable and gauge invariant with respect to the SM gauge group contains $R\!\!\!/_p$ Yukawa couplings between the supersymmetric partner of the left-handed electron $\tilde{e}_L$, a left-handed up-type quark u^j_L and a right-handed down-type anti-quark $\bar{d}^k_R$, where j and k denote generation indices. The corresponding part of the Lagrangian reads

$$\mathcal{L}_{R\!\!\!/_p} = -\lambda'_{1jk}\tilde{e}_L u^j_L \bar{d}^k_R + \text{h.c.} \tag{1}$$

At HERA, the presence of couplings λ'_{1j1} and λ'_{11k} could lead to resonant single neutralino production in e^+p and e^-p collisions, respectively, via t-channel selectron exchange, which is investigated here [a]. It is assumed that the $\tilde{\chi}^0_1$ is the next-to-lightest supersymmetric particle (NLSP) and that the decay $\tilde{\chi}^0_1 \to \gamma\tilde{G}$ occurs with an unobservably small lifetime and dominates over $R\!\!\!/_p$ neutralino decays. The resulting experimental signature which was investigated in this

[a] Resonant squark production in $R\!\!\!/_p$ SUSY has been investigated previously at HERA in models in which the LSP is either a gaugino [12] or a light squark [13]. Squark mass dependent limits on various $R\!\!\!/_p$ Yukawa couplings have been derived. In contrast, the process considered in this analysis is completely independent of the squark sector.

analysis for the first time at HERA is a photon, a jet originating from the scattered quark and missing transverse momentum due to the escaping gravitino. The main SM background arises from radiative charged current (CC) deep inelastic scattering (DIS) with a jet, a photon and a neutrino in the final state.

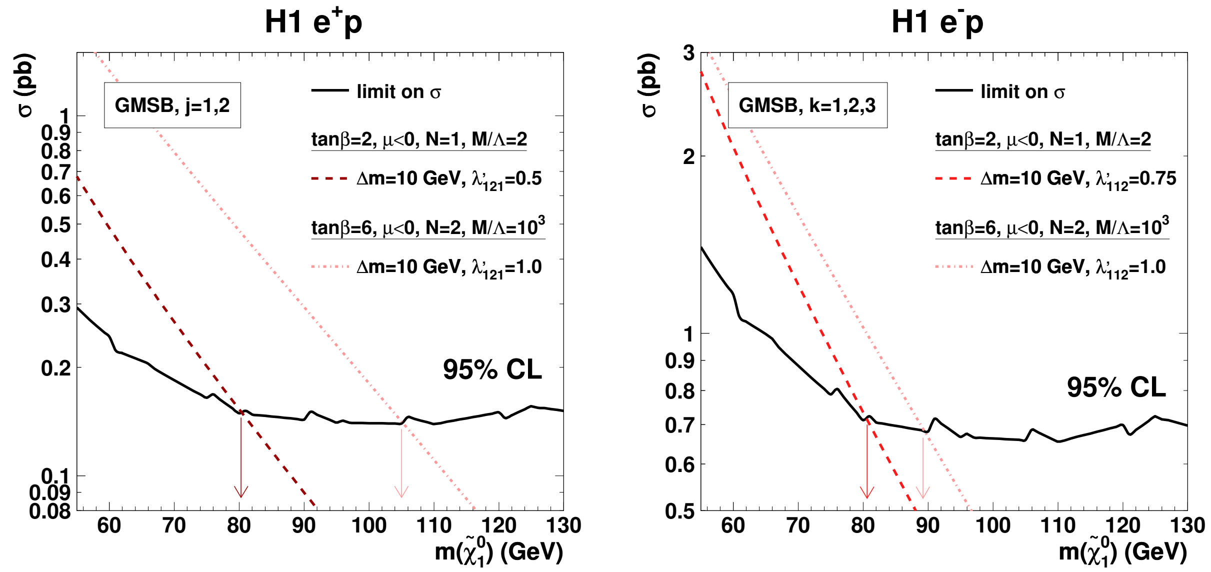

Figure 2: Upper limit at the 95 % CL on the cross section as a function of the neutralino mass for example GMSB scenarios (solid lines). For comparison, the GMSB cross sections for different $R\!\!\!/_p$ couplings λ'_{121} and λ'_{112} are superimposed for a mass difference of $\Delta m = m(\tilde{e}_L) - m(\tilde{\chi}_1^0) = 10\,\mathrm{GeV}$ (dashed and dashed-dotted lines).

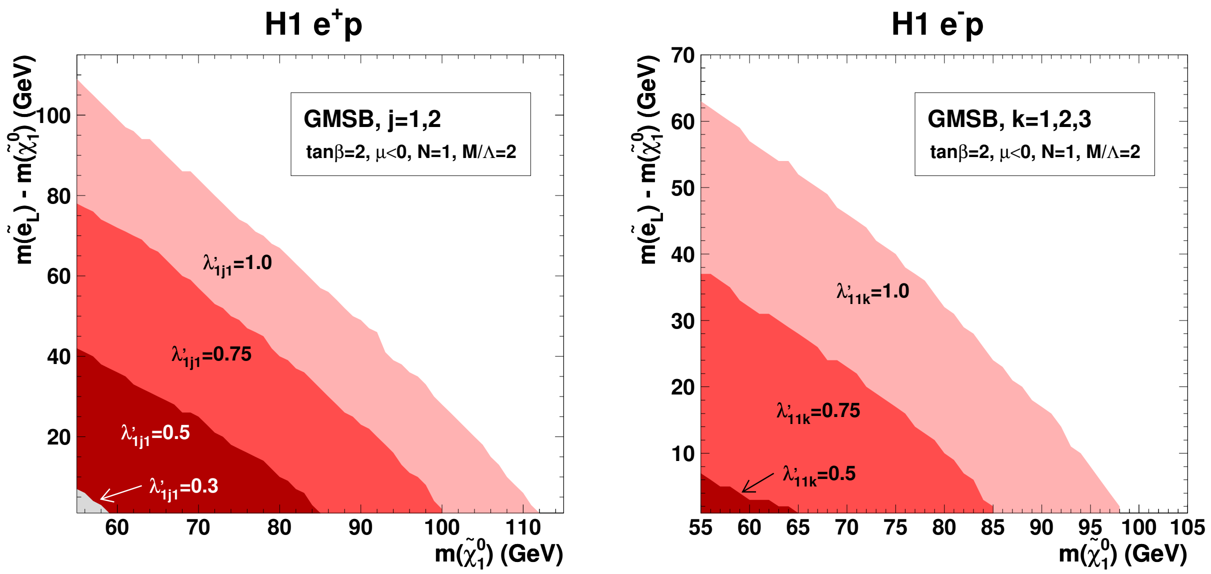

Figure 3: Excluded regions at the 95 % CL in the $\Delta m = m(\tilde{e}_L) - m(\tilde{\chi}_1^0)$ and $m(\tilde{\chi}_1^0)$ plane for various values of λ'_{1j1} $(j = 1, 2)$ and λ'_{11k} $(k = 1, 2, 3)$.

The data correspond to an integrated luminosity of $64.3\,\mathrm{pb}^{-1}$ for e^+p collisions recorded in 1999 and 2000 and $13.5\,\mathrm{pb}^{-1}$ for e^-p collisions recorded in 1998 and 1999. The data analysis reveals no deviation from the SM.

Constraints on GMSB models are derived for different values of the $R\!\!\!/_p$ coupling. In Fig. 2, upper limits on the cross sections are shown as a function of $m(\tilde{\chi}_1^0)$ for e^+p (left) and e^-p (right) collisions. The limits become less stringent at low neutralino masses due to the reduced signal detection efficiencies. Typical GMSB cross sections for different values of the couplings λ'_{121} and λ'_{112} are also shown for a mass difference $\Delta m = m(\tilde{e}_L) - m(\tilde{\chi}_1^0) = 10\,\mathrm{GeV}$.

In Fig. 3, excluded regions are presented in the plane spanned by Δm and $m(\tilde{\chi}_1^0)$ using data from e^+p (left) and e^-p collisions (right) for various values of the respective $R\!\!\!/_p$ coupling. For $\lambda'_{1j1} = 1.0$, the e^+p results exclude neutralino masses up to 112 GeV for small Δm. For large Δm and small neutralino masses, selectron masses up to 164 GeV are excluded. For masses $m(\tilde{\chi}_1^0)$ and $m(\tilde{e}_L)$ close to 55 GeV, λ'_{1j1} Yukawa couplings of electromagnetic strength are excluded. In e^-p collisions, for $\lambda'_{11k} = 1.0$, neutralino masses up to 98 GeV for small Δm and selectron masses up to 118 GeV for large Δm are ruled out. These are the first constraints from HERA on SUSY models which are independent of the squark sector.

4 Magnetic Monopoles

One of the outstanding issues in modern physics is the question of the existence of magnetic monopoles. Dirac showed that their existence leads naturally to an explanation of electric charge quantisation [14]. The quantisation of the angular momentum of a system of an electron with electric charge e and a monopole with magnetic charge g leads to Dirac's charge quantisation condition $eg = n\hbar c/2$, where $\hbar$ is Planck's constant divided by 2π, c is the speed of light and n is an integer. Within this approach, taking $n = 1$ sets the theoretical minimum magnetic charge which can be possessed by a particle (known as the Dirac magnetic charge, g_D). However, if the elementary electric charge is considered to be held by the down quark then the minimum value of this fundamental magnetic charge will be three times larger. The value of the fundamental magnetic charge could be even higher since the application of the Dirac argument to a particle possessing both electric and magnetic charge restricts the values of n to be even.

A direct search for magnetic monopoles produced in e^+p collisions at HERA has been made for the first time [3]. The beam pipe surrounding the interaction region in 1995-1997 was investigated to look for stopped magnetic monopoles. During this time an integrated luminosity of $62\,\mathrm{pb}^{-1}$ was delivered. Since the binding energy of magnetic monopoles is expected to be large in the material of the pipe (aluminium at that time) they should remain permanently trapped provided that they are stable. The beam pipe was cut into long thin strips which were each passed through a superconducting coil coupled to a Superconducting Quantum Mechanical Interference Device (SQUID) which was sensitive down to 0.1 Dirac magnetic charges ($0.1g_D$). Trapped magnetic monopoles in a strip will cause a persistent current to be induced in the superconducting coil by the magnetic field of the monopole, after complete passage of the strip through the coil. In contrast, the induced currents from the magnetic fields of the ubiquitous permanent magnetic dipole moments in the material, which can be pictured as a series of equal and opposite magnetic charges, cancel so that the current due to dipoles returns to zero after passage of the strip.

The values for the persistent current were converted to Dirac Monopole units (g_D) and are shown for different strips in Fig. 4. In the dataset of December 2002 (open circles) two of the strips measured showed persistent currents of value expected from the passage of a magnetic charge of about $+0.7g_D$. All the strips were then remeasured several times in the set of data in January 2003, shown as closed circles in Fig. 4. None of them (except a single reading for strip 3) showed a persistent current after traversal through the magnetometer. It was therefore assumed that the observed persistent currents during the first set had been caused by random jumps in the base line of the magnetometer electronics. It can be seen from Fig. 4 that none of the strips showed a persistent current which appeared consistently in more than one reading. Thus, no magnetic monopoles were observed and charge and mass dependent upper limits on the e^+p production cross section are set.

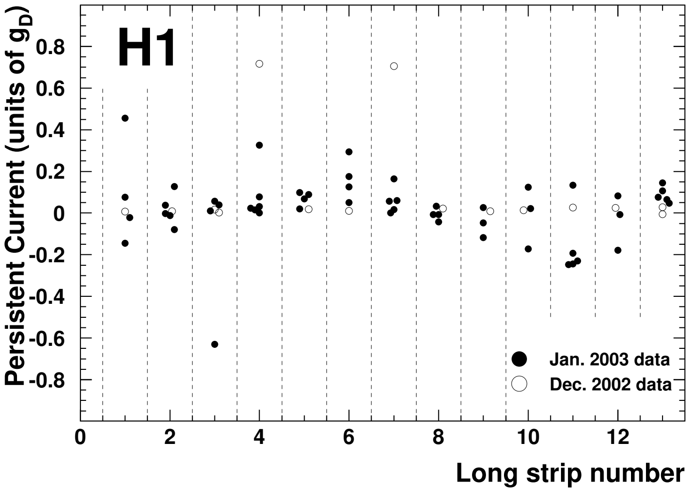

Figure 4: The measured persistent current (in units of g_D) in each strip, after passage through the magnetometer, plotted against strip number for 13 strips of the central beam pipe. Some of the strip numbers are offset for clarity. It can be seen that none of the fluctuations observed in single readings occurred consistently in other readings on the same strip showing that no trapped monopole was present.

5 General Search

The H1 collaboration has performed a general search for new phenomena by looking for deviations from the SM prediction at high transverse momentum [4]. For the first time all event topologies involving objects like electrons (e), photons (γ), muons (μ), neutrinos (ν = missing particles) and jets (j) are investigated in a single analysis. Event classes are defined consisting of at least two clearly identified and isolated objects i with a minimum transverse momentum of $p_T^i > 20\,\mathrm{GeV}$. Events were found in 22 classes. The event yields span several orders of magnitude. Overall good agreement with the SM prediction was found. In this dataset a few events were observed in the $ej\nu$ channel where the expectation, again dominated by single W production, is low.

The same analysis was repeated with the recent data taken by the H1 experiment in 2003/2004 based on an integrated luminosity of $45\,\mathrm{pb}^{-1}$. Again good overall agreement between data and the SM expectation was found, see Fig. 5 (left). In this dataset the most significant deviation was found in the $ej\nu$ channel, to which also single W production mainly contributes in the SM. The excesses observed in the $ej\nu$ and $\mu j\nu$ classes are further detailed in the next section.

6 Isolated leptons with missing transverse momentum

Events with isolated leptons and missing transverse momentum were selected by requiring an isolated high p_T lepton (electron, muon or tau) and missing transverse momentum. For the remaining hadronic final state the transverse momentum (p_T^X) is measured. In the radial plane, it is required that the hadronic final state and the lepton are not back-to-back, which reduces genuine background from deep inelastic scattering, and ensures that the missing transverse momentum is due to an invisible particle (ν). The genuine SM "background" process is single W production with a leptonic decay. For the SM prediction of this process next-to-leading order QCD corrections are implemented to the leading order MC generator [15] by a reweighting method [16]. Searches have been performed by both experiments H1 and ZEUS in the decay channels into electrons and muons [6,8], and taus [7,9].

In the HERA I analyses good agreement between data and the SM expectation was found at

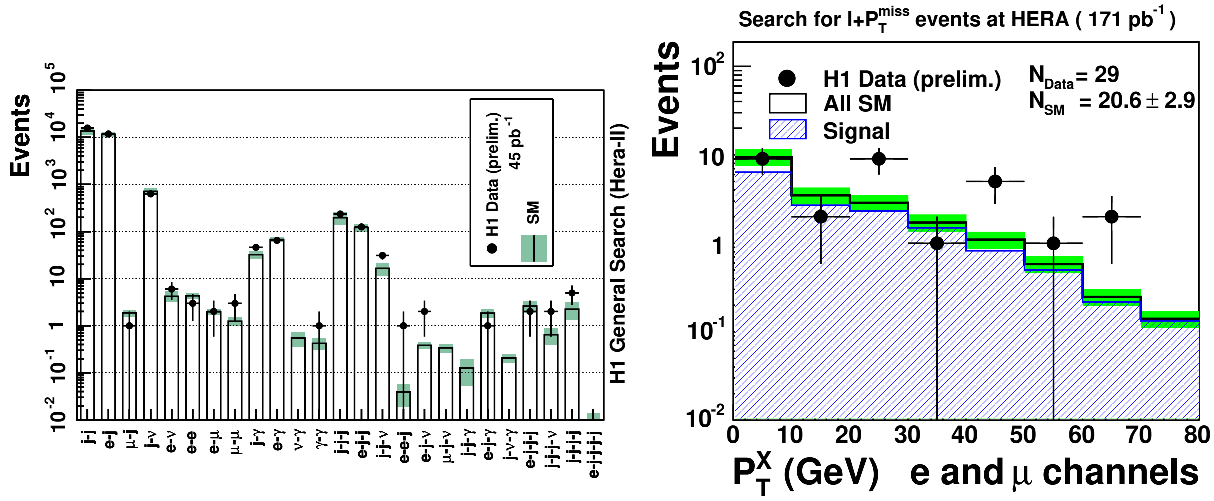

Figure 5: Left: HERA II event yields in the general search for new phenomena at high p_T. Data (points) are compared to the SM prediction (histogram bars). The uncertainty of the SM prediction is indicated by the shaded band. Right: The hadronic transverse momentum distribution in the electron and muon channels combined compared to the SM expectation (open histogram). The SM expectation is dominated by real W production (hatched histogram). The total error on the SM expectation is given by the shaded band.

Table 1: HERA I event yields in the search for isolated leptons with missing transverse momentum. The numbers are given for the electron, muon and tau channel for different cuts p_T^X.

HERA I 1994-2000	observed/expected		
H1 $\mathcal{L}(e^{\pm}p) = 118\,\mathrm{pb}^{-1}$	Electron	Muon	Tau
Full sample	11 / 11.5 ± 1.5	8 / 2.94 ± 0.50	5 / 5.81 ± 1.36
$p_T^X > 25\,\mathrm{GeV}$	**5** / 1.76 ± 0.30	**6** / 1.68 ± 0.30	0 / 0.53 ± 0.10
$p_T^X > 40\,\mathrm{GeV}$	3 / 0.66 ± 0.13	3 / 0.64 ± 0.14	0 / 0.22 ± 0.05
ZEUS $\mathcal{L}(e^{\pm}p) = 130\,\mathrm{pb}^{-1}$	Electron	Muon	Tau
Full sample	24 / 20.6 ± 3.2	12 / 11.9 ± 0.6	3 / 0.4 ± 0.12
$p_T^X > 25\,\mathrm{GeV}$	2 / $2.9^{+0.59}_{-0.32}$	5 / 2.75 ± 0.21	**2** / 0.2 ± 0.05
$p_T^X > 40\,\mathrm{GeV}$	0 / 0.94 ± 0.11	0 / $0.95^{+0.14}_{-0.10}$	1 / 0.07 ± 0.02

both experiments, see Tab. 1. However, after applying a cut $p_T^X > 25\,\mathrm{GeV}$, 11 electron and muon events were observed by the H1 experiment compared to an expectation of 3.44 ± 0.59, and 2 events were observed in the tau channel by the ZEUS collaboration compared to an expectation of 0.20 ± 0.05. Neither of these excesses were confirmed by the partner experiment.

To enhance the limited statistics isolated lepton events were investigated in the recent HERA II dataset by the H1 collaboration [5]. The analyses were repeated in the electron and muon channel. In total 10 new events were found compared to an expectation of 6.08 ± 0.92 events, see Tab. 2. For $p_T^X > 25\,\mathrm{GeV}$, 5 events — all found in the electron channel — survived compared to an expectation of 0.84 ± 0.19 in the electron and 0.85 ± 0.13 in the muon channel.

The distribution of the transverse momentum of the hadronic final state of all H1 data combined corresponding to an integrated luminosity of $171\,\mathrm{pb}^{-1}$ is shown in Fig. 5 (right). For $p_T^X > 25\,\mathrm{GeV}$ a clear excess of 16 events compared to 5.1 ± 1.0 expected is visible. However, more data and more detailed studies are required to resolve unambiguously the differences of event yields observed so far by the two collaborations H1 and ZEUS.

Table 2: HERA II event yields in the search for isolated leptons with missing transverse momentum. The numbers are given for the electron and muon channel and after combination for different cuts p_T^X.

HERA II 2003-2004	observed/expected		
H1 $\mathcal{L}(e^{\pm}p) = 53\,\mathrm{pb}^{-1}$	Electron	Muon	Combined
Full sample	9 / 4.75 ± 0.76	1 / 1.33 ± 0.19	10 / 6.08 ± 0.92
$p_T^X > 25\,\mathrm{GeV}$	**5** / 0.84 ± 0.19	0 / 0.85 ± 0.13	**5** / 1.69 ± 0.28

7 Conclusions

Results on searches for leptoquarks, light gravitinos in $\not{R}_p$ SUSY models and magnetic monopoles using the HERA I (1994-2000) $e^{\pm}p$ data have been presented. No deviation from the SM prediction was found. Since that period of data taking HERA has seen a major upgrade program to provide higher luminosities and longitudinally polarised $e^{\pm}$ beams and first data have been taken. Recent results including HERA II (2003/2004) e^+p data on a general model independent search and on a search for isolated lepton events with missing transverse momentum have been discussed. The trend of H1 at HERA I detecting more isolated lepton events than predicted seems also to continue at HERA II in the electron channel. At present, given the available statistics of isolated lepton events collected at the H1 and ZEUS experiments, the results are inconclusive and clearly more data, which are going to be collected in the upcoming years, will help to solve the puzzle.

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