Beyond the Standard Model at HERA

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Abstract. The prospects of physics beyond the standard model in deep inelastic scattering are reviewed, emphasizing the search for contact interactions, for leptoquarks and for supersymmetry with R-parity violation. R-parity violating supersymmetry is explored as a speculative source of events with high energy muons and missing transverse momentum, but no convincing explanation for events of this type observed at H1 is found.

1 Introduction

The luminosity delivered to the experiments at HERA has now become large enough to open a new focus of physics analyses looking at processes with cross sections of the order of 1 pb and below. This is the typical value for neutral and charged current (NC and CC) cross sections at large values of Bjorken x and momentum transfer Q^2. Also measurements of rare standard model (SM) processes like the production of an additional gauge boson, are becoming possible. These low cross section processes provide a wealth of possibilities to look for deviations from the standard model predictions and constitute important backgrounds for searches for physics beyond the standard model [1].

The motivation to search for new physics at HERA has received a strong impetus by the observation of enhancements of cross sections at several places. The excess of events at large x and large Q^2 in NC and CC scattering [2] observed in the 1994–96 e^+p data has been discussed at length in the literature (see [3,4] and references therein). A similar excess was not observed in the 1997 data so that the significance in the complete 1994–97 data sample is reduced, but still there: in the mass bin $200\,\mathrm{GeV}\pm\Delta M/2$ ($\Delta M = 25\,\mathrm{GeV}$) and for $y > 0.4$, H1 observed 8 events, but only 2.87 ± 0.48 are expected (see Fig. 1a). In the CC channel the observed number of events is in agreement with the SM predictions within the uncertainties: H1 observed 7 events with $Q^2 > 15,000\,\mathrm{GeV}^2$ (4.8 ± 1.4 expected) and ZEUS found 2 with $Q^2 > 35,000\,\mathrm{GeV}^2$ (0.29 ± 0.02 expected), both in the 1994–96 data set. Notably the occurrence of five events with an isolated muon and large missing transverse momentum at H1 [5] which are seemingly not all a sign of W production presents a challenge for the understanding of the experiments.

In the following, I selected some of the alternatives to standard model physics which, if realized in nature, have a good chance to be discovered at HERA. If not, HERA is expected to significantly contribute to setting limits on their respective

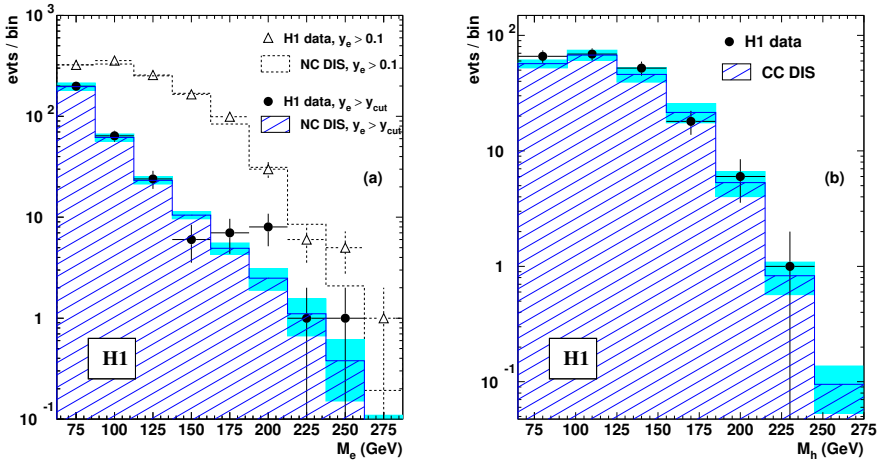

Fig. 1. Mass spectra for NC (left) and CC (right) DIS-like events for data (symbols) and SM expectation (histograms) observed at H1 in $37\,\mathrm{pb}^{-1}$ of e^+p data taken in 1994–1997 [6]

model parameters. Other related topics of interest have been discussed previously in Refs. [1,7].

2 New Physics Scenarios

Despite of the great success of the standard model, various conceptual problems provide a strong motivation to look for extensions and alternatives. Two main classes of frameworks can be identified among the many new physics scenarios discussed in the literature:

- Parametrizations of more general interaction terms in the Lagrangian like contact interactions or anomalous couplings of gauge bosons are helpful in order to *quantify the agreement* of standard model predictions with experimental results. In the event that deviations are observed, they provide a framework allowing to relate different experiments and cross-check possible theoretical interpretations. Being insufficient by themselves, e.g. because they are not renormalizable, parametrizations are expected to show the directions to the correct underlying theory if deviations are observed.
- Models, sometimes even complete theories, provide specific frameworks that allow a consistent derivation of cross sections for conventional and new processes. Examples are the two-Higgs-doublet extension of the standard model, grand unified theories and, most importantly, supersymmetry with or without R-parity violation.

The following examples attained most interest when the excess of large-Q^2 events at HERA was made public [3,4].

2.1 Contact interactions

The contact interaction (CI) scenario relevant for NC processes assumes that 4-fermion processes are modified by additional terms in the interaction Lagrangian of the form

$$\mathcal{L}_{\mathrm{CI}} = \sum_{\substack{i,k=L,R \\ q=u,d,\cdots}} \eta^q_{ik} \frac{4\pi}{(\Lambda^q_{ik})^2} (\bar{e}_i \gamma^\mu e_i)(\bar{q}_k \gamma_\mu q_k) \ . \tag{1}$$

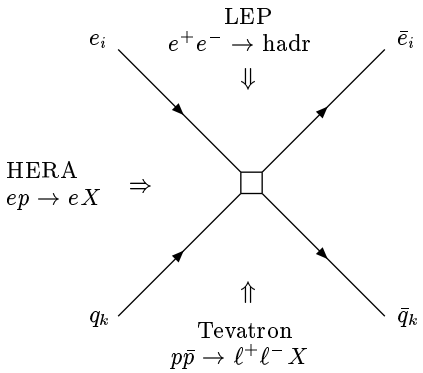

Fig. 2. Schematic view of a contact interaction term.

Similar terms with 4-quark interactions would be relevant for new physics searches at the Tevatron and 4-lepton terms would affect purely leptonic interactions[1]. In equation (1), as is usual practice, only products of vector or axial-vector currents are taken into account since limits on scalar or tensor interactions are very stringent. Such terms are motivated in many extensions of the standard model as effective interactions after having integrated out new physics degrees of freedom like heavy gauge bosons, leptoquarks and others, with masses beyond the production threshold. The normalization with the factor 4π is reminiscent of models which predict CI terms emerging from strong interactions at a large mass scale Λ.

Equation 1 predicts modifications of cross sections for processes involving two leptons and two quarks in all channels as visualized in Fig. 2. Both enhancement or suppression are expected, depending on the helicity structure of the contact term and its sign η^q_{ik}. If the CI mass scale is large, the highest sensitivity is expected at experiments with highest energies, but due to the extremely high experimental precision, also atomic parity violation experiments at low energies are sensitive to parity-odd combinations of helicities [10].

Limits from single experiments at the Tevatron, HERA or LEP2 for models with one single parameter [11] are typically in the order of several TeV and

[1] Contact interactions modifying CC processes can be constructed in a similar way and have been investigated in Refs. [8,9].

all present high-energy experiments have achieved limits in a very similar mass range despite of their different center-of-mass energies. Consequently, with a signal at HERA one should expect visible effects at LEP2 and at the Tevatron. Moreover, global fits taking into account experimental data from these different sources give valuable additional insight. Recent global fits [12,13] have taken into account new data from HERA, LEP2, Tevatron and CCFR. The resulting limits for single-parameter models increase from the range 1.8–10.5 TeV (derived from a single experiment) to 5.1–18.2 TeV (derived from the global analysis) [12]. In a general model where 8 independent parameters are allowed to be non-zero at the same time, the limits are of course weaker and range from 2.1 to 5.1 TeV for the various mass scales Λ^q_{ik}. A comparison of various data obtained at LEP2, Tevatron and HERA with the prediction of a model with contact interactions as obtained in the best global fit of Ref. [12] shows that only the HERA data at highest values of Q^2 tend to support the presence of a contact term.

Assuming the presence of contact interactions with a mass scale in the range allowed by the best fit one can derive 95 % CL limits for the predicted deviations from the SM cross sections. Figure 3 shows the results for e^+p and e^-p scattering at HERA. Obviously, a possible deviation in electron scattering is much more restricted than for positron scattering; in the latter case, deviations of the cross section for $Q^2 > 15,000\,\mathrm{GeV}^2$ from the standard model of 40 % are allowed, whereas only 20 % deviations are inside the 95 % CL band for the former case. A luminosity of 100–200 pb^{-1} would suffice in e^+p scattering to observe such a deviation. On the other hand, measurements with positrons at HERA have a better chance to further improve limits on contact terms.

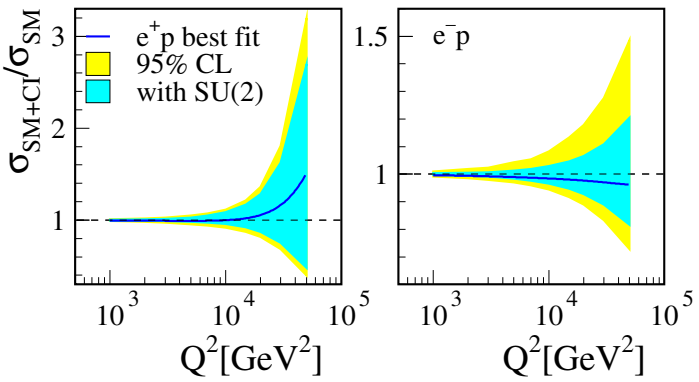

Fig. 3. The 95 % CL limit band on the ratios of e^+ and e^- cross sections for NC DIS at HERA with and without a contact term of the best fit of [14]

In the case of the observation of deviations from the standard model predictions, the combination of results obtained in different experiments and from measurements with polarized beams will be helpful to identify the helicity struc-

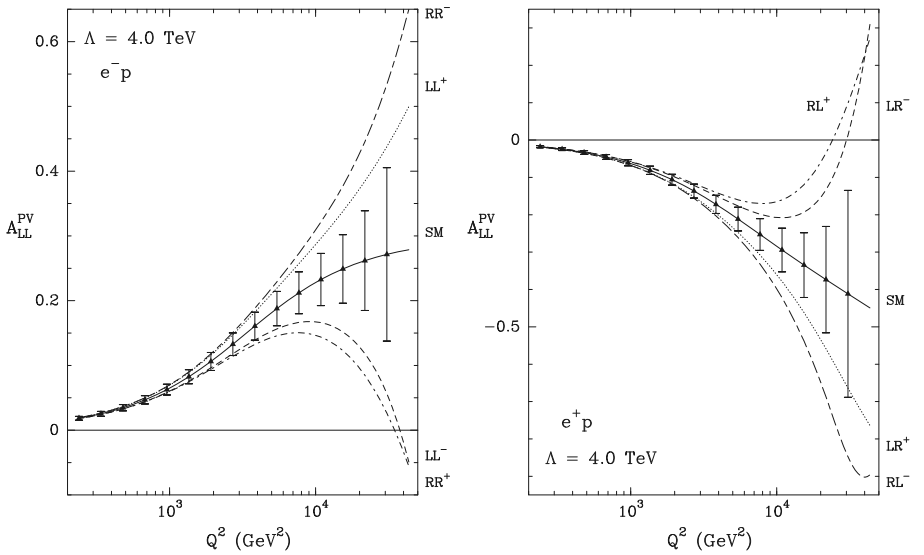

Fig. 4. Spin asymmetries $A_{LL}^{PV}(e^-)$ (left) and $A_{LL}^{PV}(e^+)$ (right). Solid lines correspond to the SM predictions; the expected errors are shown assuming a luminosity of 125 pb^{-1} for each configuration of beam polarizations. Non-solid lines correspond to CI scenarios with $\Lambda = 4$ TeV and helicities as indicated [15]

ture of contact interaction terms [15]. This is visualized in Fig. 4 where the parity-violating spin-spin asymmetries in $e^{\pm}p$ scattering are shown for models with various types of contact terms and a mass scale of $\Lambda = 4$ TeV. With an integrated luminosity of 125 pb^{-1} for each configuration of beam polarization, these models would be clearly distinguishable.

2.2 Large Extra Dimensions

In the usual contact term scenario one concentrates on interaction terms with mass dimension 6. Higher-dimension interactions are usually assumed to be less important since they would be suppressed by a higher power of the ratio of the center-of-mass energy and the mass scale characterizing these interactions. Nevertheless it is interesting to study the effect of such terms since models might exist where higher-dimensional interactions are the dominating deviation from the standard model framework. Recently, theories with large extra dimensions emerging in low-scale compactified string theories have been shown to constitute a viable alternative to the standard model [16]. A specific class of these theories would predict deviations from standard model cross sections through the exchange of gravitons and their Kaluza-Klein excitations [17]. The effect can be described with the help of dimension 8 NC contact terms [18], but there would also exist completely new kind of interactions like electron-gluon contact terms.

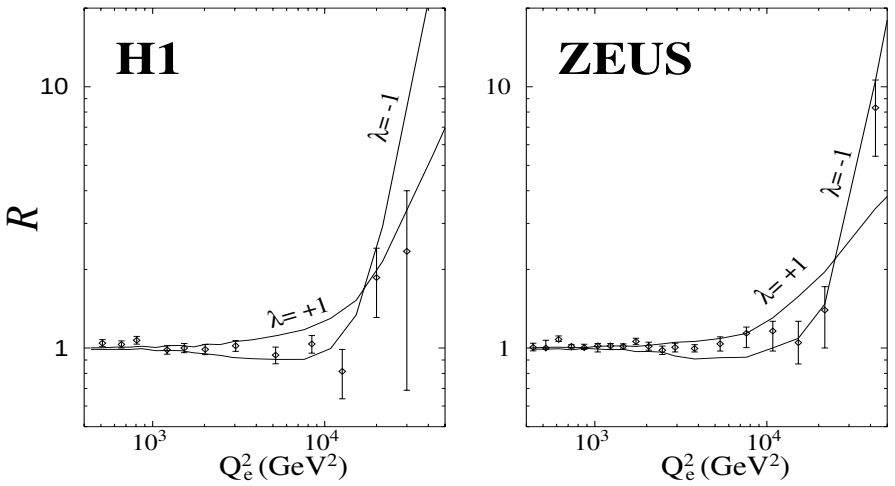

Fig. 5. Illustration of the effect of large extra dimensions on NC e^+p scattering at HERA [19]

Figure 5 shows an example [19] for the effect of graviton exchange with two choices for the relative sign of the standard model and new physics amplitudes compared to the large-Q^2 data from H1 and ZEUS. The mass scale M_s of such theories are chosen in this example to saturate the 95 % CL limits: 543 (567) GeV for H1 (ZEUS) data and $\lambda = +1$ and 436 (485) GeV for $\lambda = -1$. As discussed in [20], with an integrated luminosity of 250 pb^{-1} for each of electron and positron scattering with left- and right-handed longitudinal polarization (i.e. 1 fb^{-1} in total), HERA could set limits slightly above 1 TeV and would thus be competitive with LEP2 (expected 1.1 TeV 95 % CL limit), but slightly worse than the Tevatron (1.3 TeV). A future e^+e^- linear collider would be sensitive to mass scales above 4 TeV and the LHC can be expected to shift the corresponding limit to 6.0 TeV [20].

2.3 Leptoquarks

Leptoquarks appear in extensions of the standard model involving unification, technicolor, compositeness, or R-parity violating supersymmetry. In addition to their couplings to the standard model gauge bosons, leptoquarks have Yukawa-type couplings to lepton-quark pairs which allow their resonant production in ep scattering. The generally adopted BRW-framework [21] is based on only a few assumptions concerning these Yukawa interactions which lead to a rather restricted set of allowed states and the branching fractions β_e for their decay to a charged lepton final state can only be 1, 0.5, or 0. States which can be produced in e^+u or e^+d scattering have $\beta_e = 1$ and for masses below 242 GeV they are excluded by Tevatron bounds.

Renewed theoretical work on the phenomenology of leptoquarks (see [4] and references therein) was initiated by the observation of an excess of events at large x and large Q^2 in the 1994–96 HERA e^+p data which showed that the BRW-framework may indeed be too restrictive. The crucial and least well motivated assumption there is that leptoquarks are not allowed to have other interactions besides their gauge and Yukawa couplings. In fact, most concrete models with leptoquarks do predict additional interactions which may lead to decay modes to other than lepton-quark final states. This would be interesting since for example the Tevatron bounds do not exclude leptoquarks with masses above 200 GeV in scenarios with branching ratios $\beta_e \lesssim 0.7$ [3,23].

A few examples for more general scenarios have been discussed in detail in the literature. In Ref. [24] a model was proposed where two leptoquark states show mixing induced by coupling them to the standard model Higgs boson. Alternatively, interactions to new heavy fields might exist which, after integrating them out, could lead to leptoquark Yukawa couplings as an effective interaction [8], bypassing this way renormalizability as a condition since this is assumed to be restored at higher energies. In the more systematic study of Ref. [23], LQ couplings arise from mixing of standard model fermions with new heavy fermions with vector-like couplings and taking into account a coupling to the standard model Higgs. The most interesting extension of the generic leptoquark

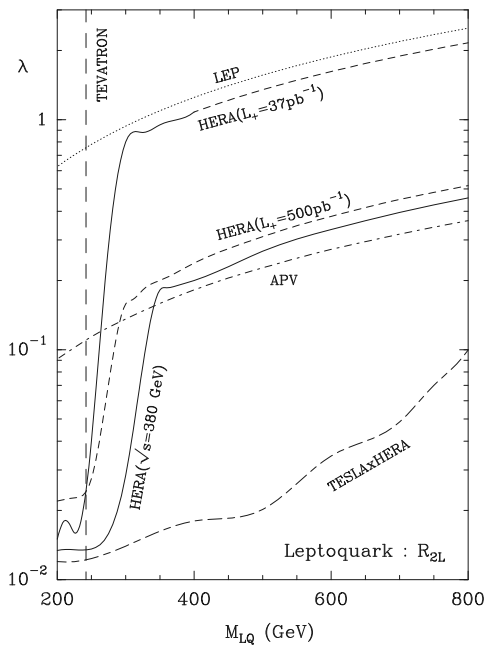

Fig. 6. Discovery limits for a scalar leptoquark at various collider experiments [27]

scenario is, however, R_p-violating supersymmetry which is discussed in the next subsection.

Searches at HERA [25] are essential to exclude such more general scenarios. Despite of the strong dependence on the lepton-quark-LQ Yukawa coupling λ, exclusion limits from HERA experiments cover much larger mass values for small λ than those obtained from indirect searches at LEP2. Since the dependence on the branching ratio in more general scenarios can be reduced considerably by combining NC and CC data, HERA limits also supersede those from Tevatron for small β_e. The most recent published limits from H1 [6] take into account the finite width of LQ states and the interference of their production amplitude with the standard model background, both effects which turned out to be non-negligible for very large LQ masses. Scalar leptoquarks with masses up to 275 GeV and vector states up to 284 GeV are excluded at 95 % CL for $\lambda = e$ [6]. Similar mass exclusion regions have been reported by ZEUS at recent conferences [26]. As shown in Fig. 6 [27], exclusion limits for the coupling λ at the same LQ mass values can expected to be reduced by a factor of ~ 5 with 500 pb^{-1} of e^+p data. With this luminosity, limits on λ for much larger LQ masses from HERA will also come close to the limits following from atomic parity violation experiments via the corresponding induced contact interactions. To further extend the search to large LQ-masses and small Yukawa couplings, an increase of the center-of-mass energy of ep collisions (for example like at TESLA$\times$HERA) would be essential.

2.4 R_p-violating supersymmetry

The Lagrangian of a supersymmetric version of the standard model may contain a superpotential of the form

$$\begin{aligned} W_{\not R_p} = \quad & \lambda_{ijk} L_i L_j E^c_k && \not L \\ & +\lambda'_{ijk} L_i Q_j D^c_k && \not L \quad \text{(includes LQ-like couplings)} \\ & +\lambda''_{ijk} U^c_i D^c_j D^c_k && \not B \end{aligned} \tag{2}$$

L_i and Q_i are the superfields for lepton and quark doublets and E^c_i, U^c_i, D^c_i the corresponding charge-conjugated ones for charged leptons, up and down quarks, respectively and i, j, k are generation indices. The separate contributions in $W_{\not R_p}$ violate lepton or baryon number conservation as indicated. Imposing symmetry under R-parity (defined as $R_p = (-1)^{3B+L+2S}$, $= 1$ for particles and $= -1$ for their superpartners) forbids the presence of $W_{\not R_p}$. The phenomenology of supersymmetry with R_p symmetry has been searched for at all present high energy experiments and HERA may set interesting limits which are complementary to those obtained at the Tevatron [1].

Many low- and high-energy experiments put limits on the couplings contained in $W_{\not R_p}$ [28]; however, they do not forbid interactions of the form $L_i Q_j D^c_k$ proportional to λ'_{ijk} in general, provided the λ''_{ijk} are chosen to be zero at the same time. This makes squarks appear as leptoquarks which can be produced on resonance in lepton-quark scattering. In contrast to the generic leptoquark scenarios described above, squarks do not only decay into lepton-quark final states

via their R_p-violating interactions but they can also decay into final states involving gauge bosons or gauginos. These R_p-conserving decays lead to a large number of interesting and distinct signatures (see [29] and references therein)[2]. Characteristically one expects multi-lepton and multi-jet final states. Mass and coupling parameters of R_p-violating supersymmetry can be varied such that the branching ratio β_e for the decay into final states with charged leptons becomes small. In this case, the strict mass limits from Tevatron would not exclude the existence of squarks in the mass range accessible to HERA. In fact, searches at HERA have not found a signal and bounds on some of the λ' couplings have been derived from searches for the characteristic lepton + multijet final states which supersede previous exclusion limits [25].

Most of the analyses done so far assume that only one of the couplings λ'_{ijk} is non-zero and only one squark state is in reach. A more general scenario with two light squark states has been considered in Ref. [31] where it was shown that $\tilde{t}_L$–$\tilde{t}_R$ mixing would lead to a broader x distribution than expected for single-resonance production. The possibility of having more than one $\lambda'_{ijk} \neq 0$ was noticed in Ref. [32] and deserves more theoretical study.

3 Events with Isolated $\mu + p_{T,miss}$

R_p-violating supersymmetry has also played a role in the search for explanations of the observation made by H1[3] of five events with an isolated μ and missing transverse momentum [5] (see also [33,34]). Events of this kind can originate from W production followed by the decay $W \to \mu\nu_\mu$. Their observed number is, however, larger than expected from the standard model taking into account next-to-leading-order corrections to the dominating resolved contribution from photoproduction [35]. Moreover, their kinematic properties are atypical for W production [33]. An explanation in terms of anomalous $WW\gamma$ couplings additionally has to face limits from Tevatron, LEP2 and ZEUS [36] and leaves the question open why a similar excess of events is not seen in $e + \not{p}_T$ events.

The observation of $\mu + \not{p}_T$ events could find an explanation in R_p-violating scenarios if it is assumed that a stop, $\tilde{t}$, is produced on-resonance at HERA. Figures 7 and 8 show examples for some of the possibilities. The process $ed \to \tilde{t} \to \mu d^k$ (Fig. 7a) which predicts μ but no large $\not{p}_T$ in the final state in gross disagreement with the experimental observation, requires two different non-zero λ' couplings [32]. The relevant product $\lambda'_{1j1}\lambda'_{2jk}$ would induce flavor changing neutral currents and is therefore limited to small values for 1st and 2nd generation quarks in the final state [40]. The analogous process with a τ replacing the μ but followed by the decay $\tau \to \mu\nu_\tau\bar{\nu}_\mu$ could also not serve as an explanation since the decay-μ would be strongly boosted in the direction of the τ, i.e. the missing transverse momentum would be correlated with the observed μ in contrast to the kinematic properties of the H1 events. Moreover, hadronic decays of the τ

[2] Monte Carlo tools needed in searches for R_p-violating supersymmetry at HERA have been improved recently [30].

[3] No event of this type was observed by ZEUS [36].

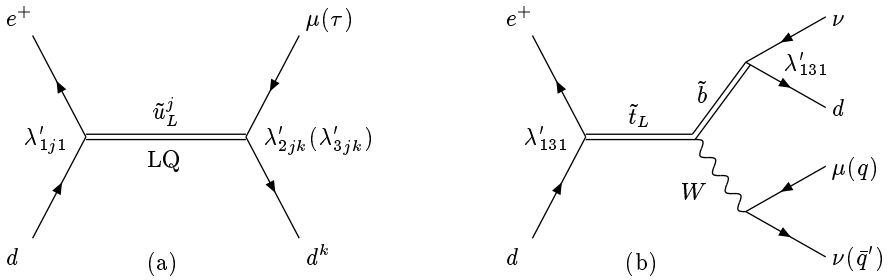

Fig. 7. Possible decays of squarks produced in e^+d scattering with R_p-violating couplings leading to isolated μ + jet final states: (a) $\tilde{u}_L^j \to \mu d_k$ through $\lambda'_{2jk} \neq 0$; (b) $\tilde{t} \to \tilde{b}W$ followed by $\tilde{b} \to \nu d$ via $\lambda'_{131} \neq 0$ and $W \to \mu^+\nu_\mu$ or $W \to 2$ jets [37].

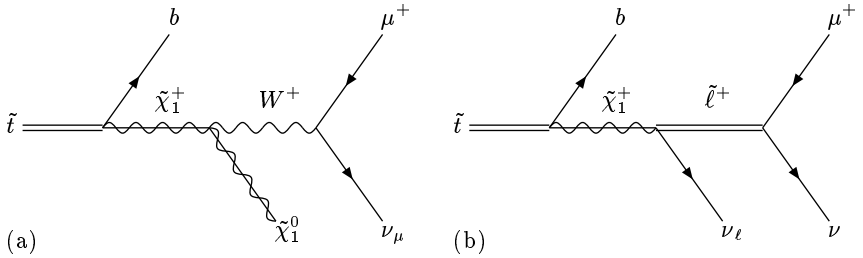

Fig. 8. Possible decay chains of the stop leading to isolated muon + jet + missing p_T: $\tilde{t} \to b\tilde{\chi}_1^+$ followed by (a) $\tilde{\chi}_1^+ \to \tilde{\chi}_1^0\mu^+\nu_\mu$ [38]; (b) $\tilde{\chi}_1^+ \to \nu_\ell\mu^+\nu$ [39].

would lead to an additional outstanding experimental signature and a search for it at H1 was negative [6].

The scenario shown in Fig. 7b [37] requires a relatively light b squark with $m_{\tilde{b}} \lesssim 120\,\mathrm{GeV}$, and some fine-tuning in order to avoid too large effects on $\Delta\rho$ in electroweak precision measurements. It could be identified by the simultaneous presence of final states with $\not{p}_T$ and multi-jets from hadronic decays of the W. Also the cascade decay shown in Fig. 8a [38] involving R_p-violation only for the production of the $\tilde{t}$ resonance, not for its decay, seems difficult to be achievable since it requires both a light chargino and a long-lived neutralino. This, as well as the even more speculative process shown in Fig. 8b [39] which requires R_p-violation in the $L_iL_jE_k^c$ sector ($\lambda_{ijk} \neq 0$) as well, can be checked from the event kinematics: assuming a value for the mass of the decaying $\tilde{t}$, the recoil mass distribution must cluster at a fixed value, the chargino mass.

These speculations on a possible origin of the observed events within R_p-violating supersymmetry are all linked to the presence of an excess of events in NC scattering. The basic assumption is that a squark, preferably a stop, is produced on-resonance; non-resonant stop production would be too much suppressed. Another type of explanation not relying on this assumption was proposed in Ref. [41]. Events of the observed type could emerge after the production of a single top quark followed by the decay chain $t \to bW$ and $W \to \mu\nu$. The cross section of SM top production would be much too small to explain the

number of observed events, but the presence of a coupling of the type of an anomalous-magnetic moment inducing the transition $c \to t$ could enhance the cross section considerably. However, the event rate would be still too small unless a non-standard large x-behavior of the charm distribution would be present, in addition. This scenario thus requires to open two new fronts of non-standard physics.

4 Concluding remarks

There are many scenarios of new physics for which deep inelastic scattering experiments are most suitable to search for. Limits on leptoquark of squark masses and their Yukawa or R-parity violating couplings obtained at HERA will stay superior to those from other experiments in many cases.

The search for new physics effects relies in most cases on trustworthy predictions from the standard model. In deep inelastic scattering this includes the necessity to know parton distribution functions as precisely as possible. It is therefore a mandatory though nontrivial task to combine the information from all available different experiments in order not to run the risk of confusing modifications of parton distributions with signs of new physics. With this in mind, the huge amount of data expected from HERA experiments in the future is guaranteed to play an indispensable role in the search for new physics — even in those cases where the most stringent limits are obtained at other experiments.

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