SEARCHES FOR NEW PHYSICS AT HERA

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(on behalf of the H1 and ZEUS Collaborations)

Abstract

Recent results from searches for new physics at HERA are reviewed. Exploiting the uniqueness of lepton-hadron collisions at high energy, searches are performed for electron-quark resonant states (leptoquarks or squarks in R-parity-violating supersymmetry) or excited states of fermions. New phenomena at a very high energy scale, manifested at present energies as effective four-fermion contact interaction, are also investigated, including cases with lepton-flavor violation. Finally, the status of events with a high-energy lepton and missing transverse momentum is presented, resulting in the most stringent constraint on the flavor-changing neutral current t-u-γ coupling which could yield single-top production.

1 Introduction

HERA collides an electron or positron beam of 27.5 GeV and a proton beam of 920 GeV (820 GeV until 1997), yielding 318 GeV (300 GeV) center-of-mass energy ($\sqrt{s}$). The square of the momentum transfer (Q^2) in deep inelastic scattering (DIS) can reach several times 10^4 GeV^2, which means that the structure of the proton is probed with a wavelength as small as one thousandth (10^{-16} cm) of its radius.

During the years 1994-2000, each of the two collider experiments, H1 and ZEUS, has collected approximately 110 pb^{-1} of e^+p and 15 pb^{-1} of e^-p data. With these data, the experiments are sensitive to rare processes with a cross section of a fraction of a picobarn, and searches for exotic signals of physics beyond the Standard Model (SM) are extensively performed. Possible signals of new physics include:

- Resonant states formed by electron-quark fusion. Examples of such states are leptoquarks or squarks (superpartners of quarks) in supersymmetry (SUSY) with R-parity violation. On-shell production of such particles is possible for those with masses up to $\sqrt{s}$.

- Physics at a much higher energy scale than the HERA energy could cause a virtual effect in electron-proton scattering in the highest-Q^2 domain. Such an effect is modeled as an effective four-fermion ($eeqq$) contact interaction. A variant of such a phenomenon is a lepton-flavor-violating (LFV) interaction in which the incoming electron changes its flavor to one of the higher-generation leptons (μ or τ).

- If the fermions (leptons and/or quarks) are composite rather than elementary, excited states of fermions could be produced as a consequence of the large momentum transfer, if the masses of such states are below the HERA $\sqrt{s}$. Such excited fermions could decay back to the ground state (normal fermions) "radiatively" by emitting a gauge boson (γ, W, Z or gluon).

In the following sections, recent results are presented from both collaborations on these topics. Most of the results are preliminary.

2 Leptoquarks

Leptoquarks (LQs) are particles which carry both lepton (L) and baryon (B) numbers. They appear in many unifying theories which try to establish fundamental relations between leptons and quarks. If LQs with a mass below the $\sqrt{s}$ of HERA

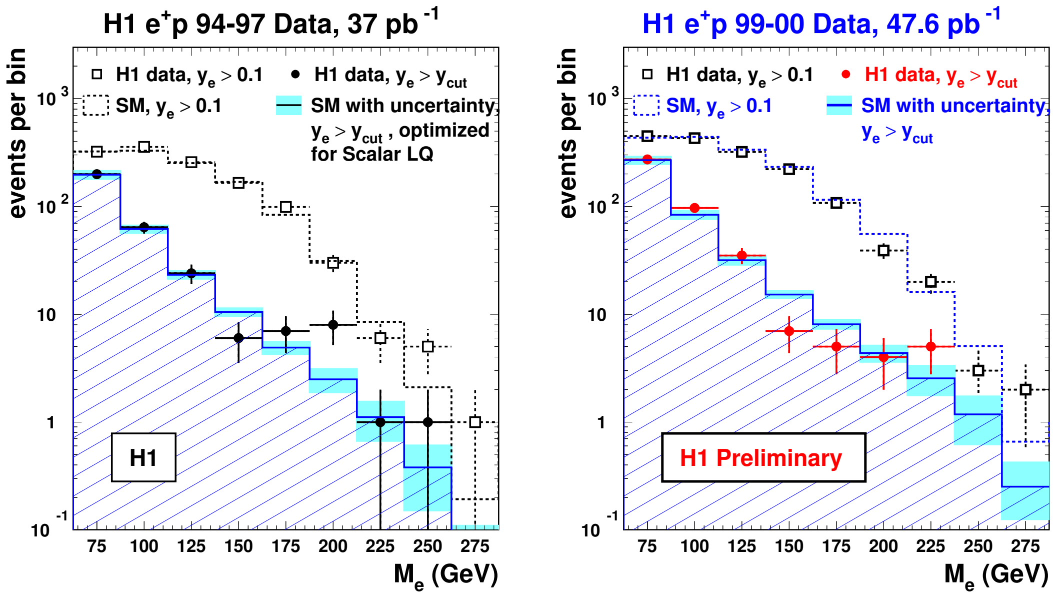

Figure 1: *Mass distribution of NC DIS candidates in H1 e^+p data from old (left) and new (right) running. Distributions before and after the y cut designed to enhance a scalar LQ signal are shown, and compared with SM predictions.*

exist, they could be directly produced via a fusion between the electron and a quark in the proton. The production cross section depends on the unknown Yukawa coupling λ at the LQ-electron-quark vertex. To evaluate the experimental results, the theoretical framework of Buchmüller-Rückl-Wyler (BRW) [1] is often used. In this framework, LQs decay to an electron-quark pair with a fixed branching ratio of either 1/2 or 1, depending on the LQ species. The only other possible decay mode is into a neutrino-quark pair.

When the LQ decays to an electron-quark pair, the final state is identical to SM neutral current (NC) DIS. However, the angular distribution is different. NC DIS with t-channel photon exchange has a $1/y^2$ angular distribution, where y is the inelasticity variable related to the electron decay angle in the e-q rest frame, θ^*, with $\cos\theta^* = 1 - 2y$. On the other hand, scalar LQs have flat y distribution and vector LQs have $(1-y)^2$ dependence. Therefore, a cut in y (or $\cos\theta^*$) is used to enhance the LQ signal among the NC DIS background.

Figure 1 shows the mass distribution of NC DIS candidates from the H1 experiment. There was an excess of events after a y cut in the old e^+p data [2], which is not confirmed by the new e^+p data taken at higher $\sqrt{s}$ [3]. ZEUS also had a small excess in the high-x, high-y region (x is the Bjorken scaling variable, related to the

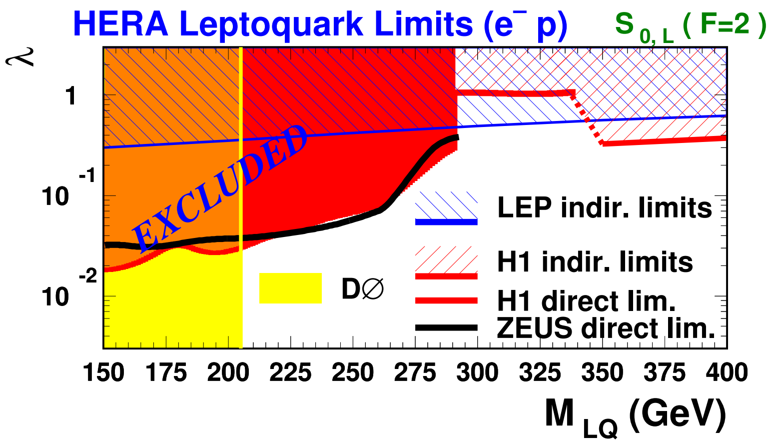

Figure 2: *Limits on the Yukawa coupling as a function of LQ mass for F=2 LQ S_0^L. Limits from the TeVatron and LEP are also shown.*

mass of the eq system via $M=\sqrt{sx}$) in the old data, which also is not confirmed by the new data [4]. With the smaller amount of e^-p data already analyzed, both experiments have observed good agreement with SM predictions [5].

With no evidence of a signal, limits are derived on the Yukawa coupling as a function of the LQ mass, as shown in Fig. 2. Note that e^+p and e^-p data have complementary sensitivity to different LQ species; e^+p collisions mainly probe the production of F=0 LQs, which couple to a positron and a valence quark (F is the fermion number, defined as F=L+3B), and correspondingly e^-p for F=2. In the figure, comparison is made with other collider results. At the TeVatron, LQs can be pair-produced and thus the limit on mass is independent of λ. The limits from LEP come from hadronic cross section measurements in which LQ exchange can produce virtual effects.

One can also consider a general case and treat the LQ branching ratio to eq as a free parameter, in contrast to the restrictions of the BRW framework. In Fig. 3, the search results in both NC (electron-jet resonance) and CC (neutrino-jet resonance) channels are used, and combined limits are obtained assuming the branching ratios to eq and νq decays sum up to one [6]. The limits in LQ mass for fixed values of λ are largely independent of how the branching ratios are shared, while the TeVatron limits degrade largely when the LQ predominantly decays to νq.

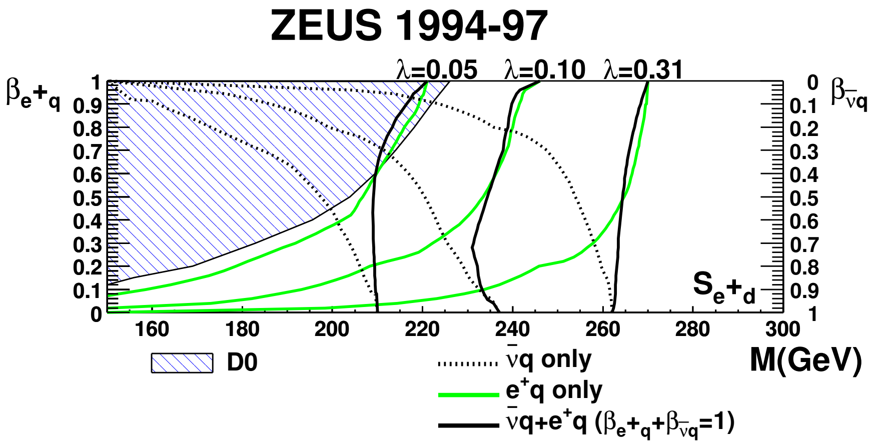

Figure 3: *Excluded region in the plane of decay branching ratio β and LQ mass M, for a scalar LQ coupling to e^+d. Limits from an e-jet analysis only (left vertical axis), a ν-jet analysis only (right vertical axis) and also by combining the two decay channels (assuming no other decay mode) are shown for three values of the Yukawa coupling. Also the limits from the TeVatron are shown. In all cases, the regions to the left of the curves are excluded.*

3 Squarks in supersymmetry with R-parity violation

R-parity is a multiplicative quantum number defined as $(-1)^{L+3B+2S}$, where S is the spin of the particle. It takes the value $+1$ for usual particles and -1 for their superpartners. In the Minimal Supersymmetric Standard Model (MSSM), R-parity is assumed to be conserved. The consequences are that superparticles are always produced in pairs, and that the lightest superparticle is stable.

However, the general supersymmetric and gauge-invariant superpotential contains three terms which violate R-parity, two with L violation and one with B violation [7]. Of particular interest at HERA is the term $\lambda'_{ijk} L_i Q_j \bar{D}_k$, where L and Q are left-handed lepton and quark doublet superfields and $\bar{D}$ is a right-handed singlet superfield of down-type quarks. The indices i, j and k denote their generation. For each generation combination, a new Yukawa coupling λ' is introduced.

With a presence of non-zero λ'_{1jk}, production of squarks is possible in eq fusion at HERA, in exact analogy to the scalar LQ production described before. However, the decay mode of the squark has more varieties than LQ decays in the BRW framework. In addition to the eq decay, a squark can decay to a quark and

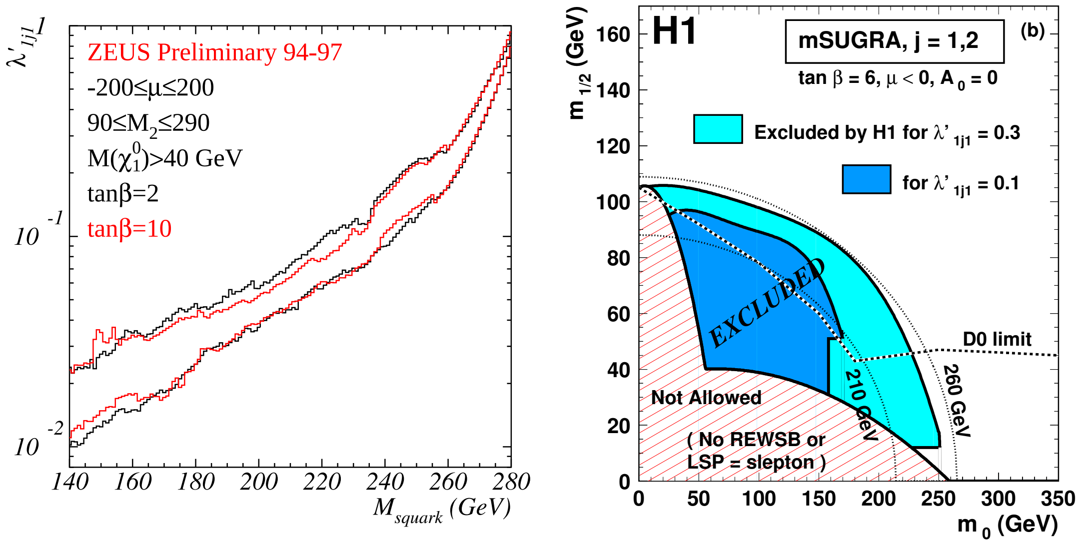

Figure 4: *On the left, ZEUS results for squarks in R-parity-violating SUSY are presented as upper limits on the λ' coupling as a function of squark mass. For two values of* $\tan\beta$*, a scan in* μ *and* M_2 *is performed, and the largest and smallest upper limits in the scan parameter space are represented by the upper and lower curves. On the right, H1 results in the mSUGRA scheme are presented, for the case of* $\tan\beta=6$*. For two values of the* λ' *coupling, excluded region in* $(m_0, m_{1/2})$ *plane is depicted, and compared with the TeVatron limit. The contours for equal squark masses are also shown.*

a gaugino with R-conserving gauge couplings. The gauginos can decay to a lepton (e or ν_e) and two quarks with the same λ' coupling, or to a lighter gaugino and two fermions with gauge couplings which results in further cascade decays. As a consequence, there are many multi-jet and/or multi-lepton final states with possible missing momentum, which compete with the simple LQ-like decays. It is worth noting that both e^+ and e^- final states are possible in the gaugino decay to eqq, which makes possible a "wrong sign" electron search with respect to the charge of the beam electron, a channel with very little background from SM processes.

Both H1 and ZEUS experiments have analyzed the e^+p data taken during 1994-97 (approx. 40 pb^{-1} per experiment) in many decay channels, and no evidence of squark production was found. The results can then be converted to constraints in SUSY parameter space under various scenarios. Figure 4 (left) shows the ZEUS results in the unconstrained MSSM framework, in which squark masses are treated

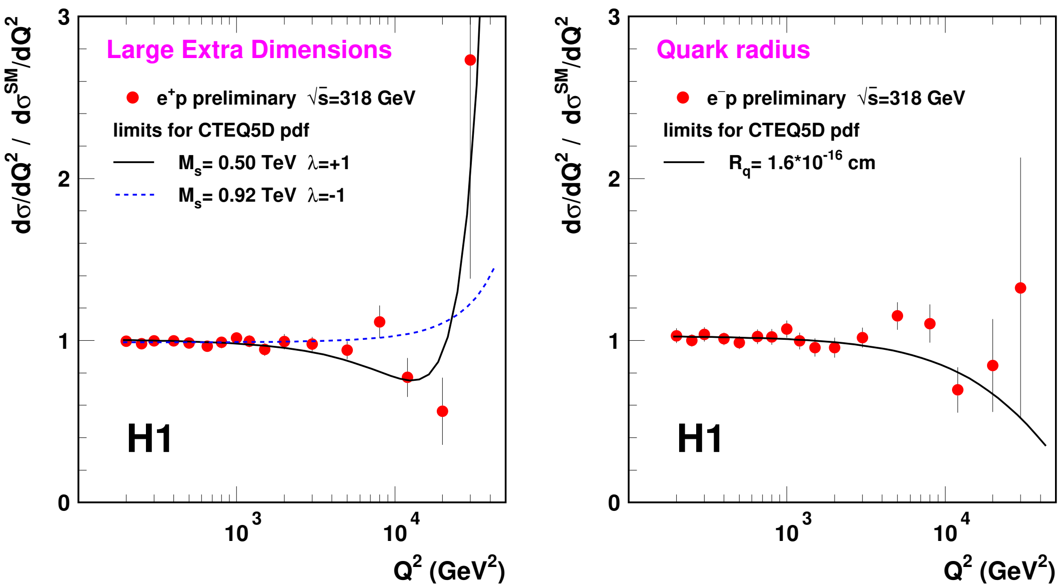

Figure 5: *Ratio of H1 e^+p NC DIS cross section to the SM prediction as a function of Q^2, overlaid with the prediction of large extra dimensions corresponding to the mass scale excluded at 95% confidence level (CL) (left), and that of e^-p overlaid with the prediction of a quark radius corresponding to the value excluded at 95% CL (right).*

as parameters independent of the MSSM parameters μ, M_2 and $\tan\beta$. For two fixed values of $\tan\beta$, a scan in the large parameter space of μ and M_2 has been performed, and upper limits in λ'_{1j1} have been obtained as a function of the squark mass [8]. The H1 collaboration has also derived limits in the mSUGRA framework, where the sparticle masses are determined from other SUSY parameters and the number of free parameters become minimal [9]. The results are presented in Fig. 4 (right). For fixed values of λ' and $\tan\beta$, the excluded region in SUSY parameter space (m_0, $m_{1/2}$) is shown. For reasonably large values of the Yukawa coupling (even as small as 0.1), HERA has a sensitivity in a region not explored at the TeVatron, although it should be mentioned that the TeVatron limits are independent of λ'.

4 Physics at very high energies

New physics at an energy scale which is much larger than the $\sqrt{s}$ of HERA could also be detected via its virtual effects at the highest-Q^2 region ($Q^2 \approx$ several 10^4 GeV^2) which corresponds to an e-q interaction at a distance as short as 0.001 fm. Such new physics processes are modeled in their low-energy limit as an effective four-fermion contact interaction (CI), and the effects are parameterized by a coupling constant, g_{CI}, and an effective mass scale, Λ.

Both collaborations [10, 11] tested the most common $eeqq$ CI models using the NC DIS data at high Q^2. Since the data are well described by the SM within statistical errors, limits are derived for each model tested. The limit on Λ depends on the chiral structure of the model, and ranges up to 9 TeV when taking the usual coupling convention $g_{CI}^2{=}4\pi$. The HERA limits are competitive and complementary to those from LEP and the TeVatron, where the tests are made in $e^+e^- \to$hadrons and Drell-Yan production, respectively.

Limits are also set on some specific models. In models with large (compactified) extra dimensions in which only the gravitational force can propagate to the extra dimensions, the fundamental Planck mass scale could be as low as the electroweak scale ($\approx$ TeV) [12]. In such models, high-energy particle collisions get additional contributions due to the exchange of a Kaluza-Klein tower of gravitons which modify the cross sections at the highest energies. This causes CI-like effects at HERA in the highest-Q^2 region with a main contribution from the interference of graviton exchange and normal NC exchange. These effects are characterized by an effective coupling $\propto \lambda/M_s^4$, where M_s is close to the fundamental Planck scale and $\lambda = \pm 1$ determines whether the interference is constructive or destructive. The results from H1 [11] are shown in Fig. 5 (left). An effective mass scale M_s of nearly 1 TeV is excluded at 95% CL.

Another example is a test of classical form factor of quarks. If one assumes that quark has a finite size and its charge is distributed with a r.m.s. of R, the NC DIS cross section gets a suppression factor $(1 - R^2Q^2/6)^2$ which dumps the cross section as Q^2 increases. Radius of the order of 10^{-16}cm is excluded, as shown in Fig. 5 (right) [11].

5 Lepton flavor violation

In the SM, lepton flavor is conserved in every interaction. However, it is not regarded as a fundamental symmetry, and new physics could naturally entail the inter-generation transition of leptons. HERA is well suited for searching for electron-muon or electron-tau LFV processes by colliding an electron with a proton at a very short distance. The final state will be an $ep \to \mu(\tau)X$ event which has a striking signature of a high-momentum muon or tau balanced by a hadronic system, which has very little background from SM processes.

Both experiments searched for such events in the 1994-97 data, with no

Table 1: *ZEUS limits (95% CL upper limit) on* $\lambda_{eq_i}\lambda_{\tau q_j}/M_{LQ}^2$ $(10^{-4}$ *GeV*$^2)$ *for F=0 LFV leptoquarks mediating the* $eq_i \leftrightarrow \tau q_j$ *transition (bold numbers in the bottom of each cell). Each row corresponds to a* (q_i, q_j) *generation combination and each column corresponds to a LQ species. The numbers in the middle of each cell are the best limit from other experiments. The cases where the ZEUS limit is the most stringent or comparable to the best limit within a factor of 2 are enclosed in a box. The * shows the cases where only the top quark can participate. Similar tables exist for F=2 LQs, and for the e-*μ *transition.*

$e \leftrightarrow \tau$				$F=0$			
$q_i q_j$	$S^L_{1/2}$ e^+u	$S^R_{1/2}$ $e^+(u+d)$	$\tilde{S}^L_{1/2}$ e^+d	V^L_0 e^+d	V^R_0 e^+d	$\tilde{V}^R_0$ e^+u	V^L_1 $e^+(\sqrt{2}u+d)$
1 1	$\tau \to \pi e$ 0.0032 **0.030**	$\tau \to \pi e$ 0.0016 **0.025**	$\tau \to \pi e$ 0.0032 **0.046**	G_F 0.002 **0.033**	$\tau \to \pi e$ 0.0016 **0.033**	$\tau \to \pi e$ 0.0016 **0.024**	G_F 0.002 **0.012**
1 2	*H1:* 0.047 $\boxed{\mathbf{0.030}}$	$\tau \to$K e 0.05 $\boxed{\mathbf{0.025}}$	$\tau \to$K e 0.05 $\boxed{\mathbf{0.046}}$	$\tau \to$K e 0.03 $\boxed{\mathbf{0.036}}$	$\tau \to$K e 0.03 $\boxed{\mathbf{0.036}}$	*H1:* 0.045 $\boxed{\mathbf{0.026}}$	K $\to \pi\nu\bar{\nu}$ $2.5 \cdot 10^{-6}$ **0.012**
1 3	*	B$\to \tau e$ X 0.08 $\boxed{\mathbf{0.049}}$	B$\to \tau e$ X 0.08 $\boxed{\mathbf{0.049}}$	B$\to l\nu$X 0.02 **0.044**	B$\to \tau e$ X 0.04 $\boxed{\mathbf{0.044}}$	*	B$\to l\nu$X 0.02 **0.044**
2 1	*H1:* 0.15 $\boxed{\mathbf{0.15}}$	$\tau \to$K e 0.05 $\boxed{\mathbf{0.092}}$	$\tau \to$K e 0.05 **0.11**	$\tau \to$K e 0.03 $\boxed{\mathbf{0.049}}$	$\tau \to$K e 0.03 $\boxed{\mathbf{0.049}}$	*H1:* 0.073 $\boxed{\mathbf{0.061}}$	K $\to \pi\nu\bar{\nu}$ $2.5 \cdot 10^{-6}$ **0.026**
2 2	$\tau \to e\gamma$ 0.03 **0.19**	$\tau \to e\gamma$ 0.02 **0.10**	*H1:* 0.13 $\boxed{\mathbf{0.12}}$	*H1:* 0.076 $\boxed{\mathbf{0.061}}$	*H1:* 0.076 $\boxed{\mathbf{0.061}}$	*H1:* 0.107 $\boxed{\mathbf{0.10}}$	*H1:* 0.044 $\boxed{\mathbf{0.041}}$
2 3	*	B$\to \tau e$ X 0.08 $\boxed{\mathbf{0.15}}$	B$\to \tau e$ X 0.08 $\boxed{\mathbf{0.15}}$	B$\to l\nu$X 0.02 **0.10**	B$\to \tau e$ X 0.04 **0.10**	*	B$\to l\nu$X 0.02 **0.10**
3 1	*	B$\to \tau e$ X 0.08 **0.16**	B$\to \tau e$ X 0.08 **0.16**	V_{ub} 0.002 **0.052**	B$\to \tau e$ X 0.04 $\boxed{\mathbf{0.052}}$	*	V_{ub} 0.002 **0.052**
3 2	*	B$\to \tau e$ X 0.08 **0.20**	B$\to \tau e$ X 0.08 **0.20**	B$\to l\nu$X 0.02 **0.073**	B$\to \tau e$ X 0.04 $\boxed{\mathbf{0.073}}$	*	B$\to l\nu$X 0.02 **0.073**
3 3	*	*H1:* 0.23 $\boxed{\mathbf{0.28}}$	*H1:* 0.23 $\boxed{\mathbf{0.28}}$	$\tau \to e\gamma$ 0.51 **0.14**	$\tau \to e\gamma$ 0.51 **0.14**	*	*H1:* 0.14 $\boxed{\mathbf{0.14}}$

candidates [2, 13]. An example of the limits are expressed in Table 1 in the context of heavy ($\gg \sqrt{s}$) LFV leptoquarks mediating the $eq \leftrightarrow lq'$ transition, for each LQ species and (q, q') generation combination. It can be seen that limits from low-energy experiments, such as rare decays, are very stringent for transitions involving first-generation quarks, but HERA has higher (or unique) sensitivity when the LFV transition involves higher-generation quarks.

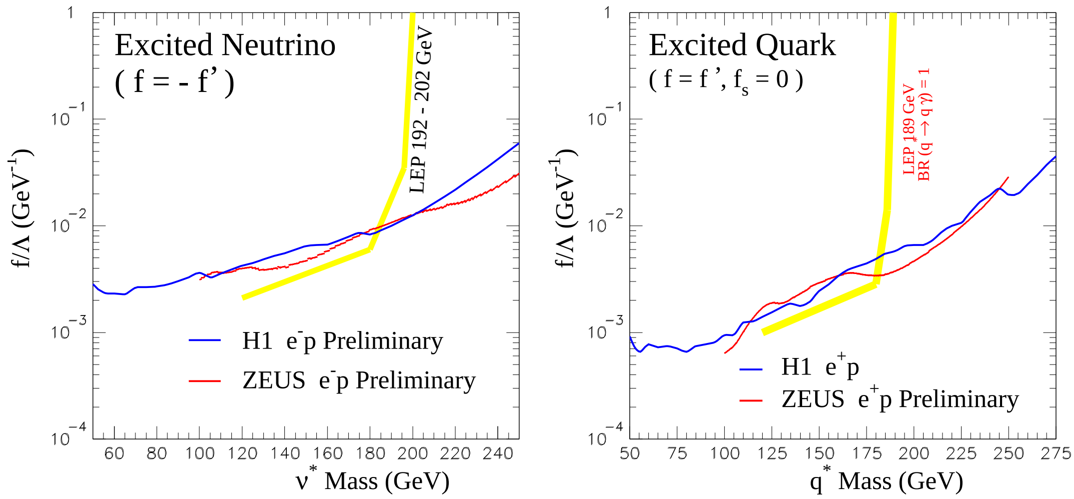

Figure 6: *Upper limits on f/Λ as a function of the excited-fermion mass for ν^* with an assumption $f{=}-f$' (left) and for q^* with an assumption $f{=}f'$, $f_s{=}0$ (right), compared to the limits from LEP.*

6 Excited fermions

If fermions are not elementary but have substructure, their excited states could be produced in a high-energy collision. At HERA, excited electrons and quarks could be produced mainly via t-channel photon exchange, and excited neutrinos via W exchange. Once produced, they can decay to a normal fermion by radiating off gauge bosons. Decays into γ, W or Z are considered here.

To measure the experimental sensitivity, the theoretical framework of Hagiwara, Komamiya and Zeppenfeld [14)] is conventionally used, in which the production cross section depends on the relative coupling strengths f, f' and f_s for the SU(2), U(1) and SU(3) gauge groups, respectively, and a common compositeness scale Λ. By assuming relations between the couplings, the decay branching ratios to different gauge bosons are fixed and the cross section depends only on the parameter f/Λ.

Both collaborations searched for excited fermions in various decay modes (including hadronic and leptonic decays of W, Z) in the 1994-97 e^+p data and 1998-99 e^-p data, with no evidence of a signal [15)]. It should be noted that e^-p collisions provide a much larger cross section for excited-neutrino production than e^+p because of the larger u-quark density in the proton and the helicity suppression in e^+p due to W-exchange.

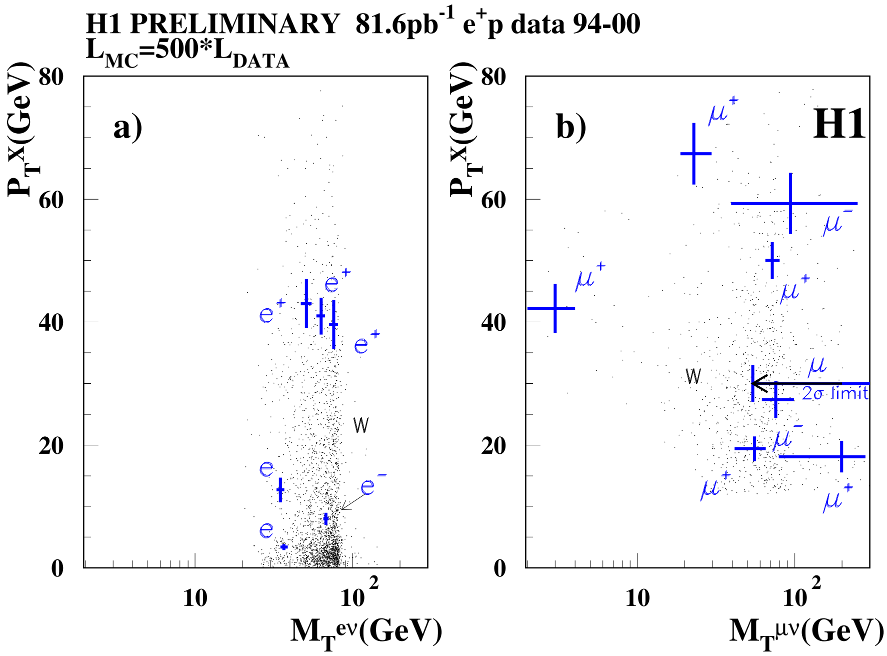

Figure 7: *Distribution of H1 events with isolated lepton and missing P_T in the plane of hadronic P_T and transverse mass. The left plot shows the electron channel and the right plot is for the muon channel. A Monte Carlo distribution of W production, with 500 times the luminosity of the data, is also overlaid.*

Figure 6 shows the upper limits obtained on f/Λ as a function of the excited-fermion mass, for ν^* and q^*. HERA experiments have a unique sensitivity beyond the LEP2 center-of-mass energy. Stringent limits on q^* are obtained from the TeVatron, but the production at the TeVatron takes place via the strong coupling f_s. HERA limits, on the other hand, are sensitive to the electroweak couplings f and f' and are thus complementary.

7 W and single-top production

Events with a high transverse momentum (high-P_T) lepton and missing P_T at HERA have drawn attention in recent years due to the excess of such events reported by the H1 experiment. When the region with large P_T^X (the transverse momentum of the remaining hadronic system) is selected, the prediction from the SM is dominated by single-W production, which has a total cross section of about 1 pb.

Figure 7 shows the results from H1 presented in summer 2000, from the e^+p data collected up to middle of 2000 [16]. Events are plotted in P_T^X and M_T, the transverse mass between the lepton and missing P_T. There is no acceptance

Table 2: *Summary of isolated high-P_T leptons from H1 (top) and ZEUS (bottom). For two values of cuts in P_T^X, the observed and expected numbers of events are shown. The numbers in parenthesis are the W contribution to the total SM expectation. For H1, the error in the expected number includes the systematic error.*

H1 preliminary 1994-2000 e^+p 82 pb^{-1}	Electrons Observed/expected (W)	Muons Observed/expected (W)
$P_T^X > 25$ GeV	3 / 1.05 ± 0.27 (0.83)	6 / 1.21 ± 0.32 (1.01)
$P_T^X > 40$ GeV	2 / 0.33 ± 0.10 (0.31)	4 / 0.46 ± 0.13(0.43)

ZEUS preliminary 1994-2000 $e^\pm p$ 130 pb^{-1}	Electrons Observed/expected (W)	Muons Observed/expected (W)
$P_T^X > 25$ GeV	1 / 1.14 ± 0.06 (1.10)	1 / 1.29 ± 0.16 (0.95)
$P_T^X > 40$ GeV	0 / 0.46 ± 0.03 (0.46)	0 / 0.50 ± 0.08 (0.41)

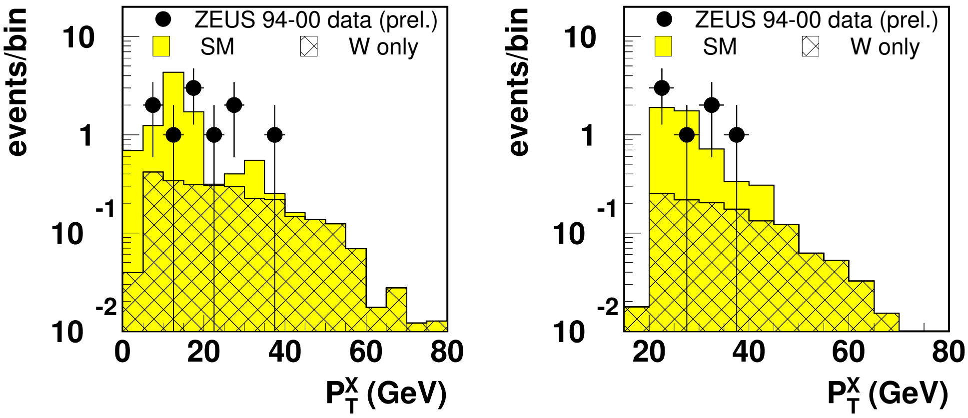

Figure 8: *P_T^X distribution of ZEUS events in the electron (left) and muon (right) channels. The shaded region in the MC expectation is the W component.*

for muon events at low P_T^X due to the requirement of missing P_T measured in the calorimeter. The observed and expected numbers of events are shown in Table 2 (top). For $P_T^X > 25$ GeV, nine electron or muon events were observed while 2.3 ± 0.6 are expected from the SM, dominated by W production.

ZEUS had observed good agreement with SM predictions for these event topologies up to the results presented in summer 2000 [17], which included data from 1994-99. In this conference, the results were updated for the first time using all of the data collected in 2000.

Figures 8 and 9 show the distributions of P_T^X and transverse mass for events with calorimeter $P_T > 20$ GeV and an isolated track with $P_T^{track} > 10$ GeV. Ten electron events and seven muon events were selected, with the SM expectation

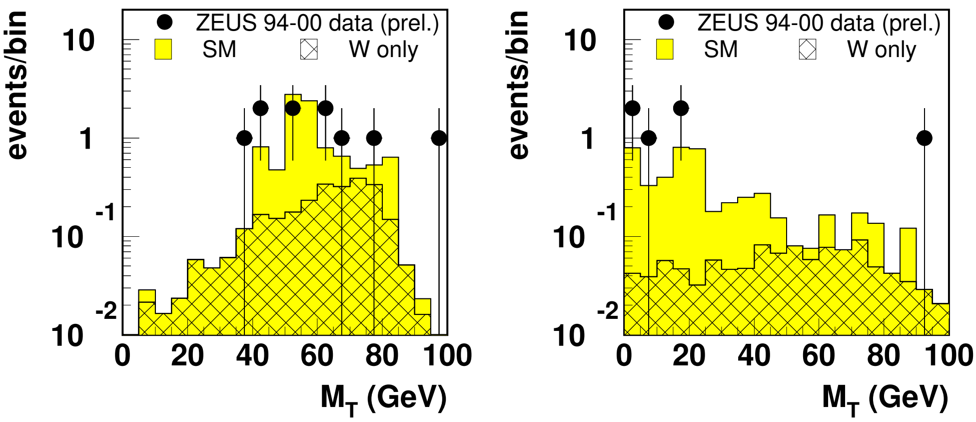

Figure 9: *Transverse-mass distribution of ZEUS events in the electron (left) and muon (right) channels. The shaded region in the MC expectation is the W component.*

being 11.0 ± 1.6 and 5.4 ± 0.7, respectively. Both the event rate and the distribution of the kinematic variables are in good agreement with SM expectations, which are dominated by NC DIS for electrons and $\gamma\gamma \to \mu\mu$ for muons.

By further applying cuts to enhance the W component in the expectation, similar to the ones used in the H1 analysis, the numbers of events are compared with the SM predictions in Table 2 (bottom) for the large-P_T^X region. In the ZEUS case, there is no excess of events observed. There is somewhat larger acceptance for W in the H1 analysis due to the wider polar-angle coverage, but it is worth mentioning that all of the observed H1 events are in the polar-angle range where ZEUS has acceptance. The muon event surviving the $P_T^X > 25$ GeV cut is from the 2000 data, and its event display is shown in Fig. 10.

An event with a lepton, missing P_T and a large P_T^X is a typical signature for a top quark decaying via $t \to bW \to bl\nu$. Therefore, the results of the searches described above can be applied to single-top production, $ep \to etX$. It is a flavor-changing neutral current (FCNC) process and highly suppressed in the SM. Any observation of single top production at HERA would be a signal for physics beyond the SM.

The resulting limits[1], together with those from LEP [18)] and the TeVatron, are expressed in Fig. 11 in the plane of two couplings, k_γ, the magnetic coupling at the photon-top-quark vertex and v_Z, the vector coupling at the Z-top-quark

[1] In the H1 single-top search, the hadronic decay of W is also used.

$P_T(\mu^+)$=38^{+20}_{-10} GeV, P_T^X=36 GeV, $Acoplanarity$=1.9, $\not{P}_T$=61^{+17}_{-8} GeV, M_T=91^{+39}_{-19} GeV

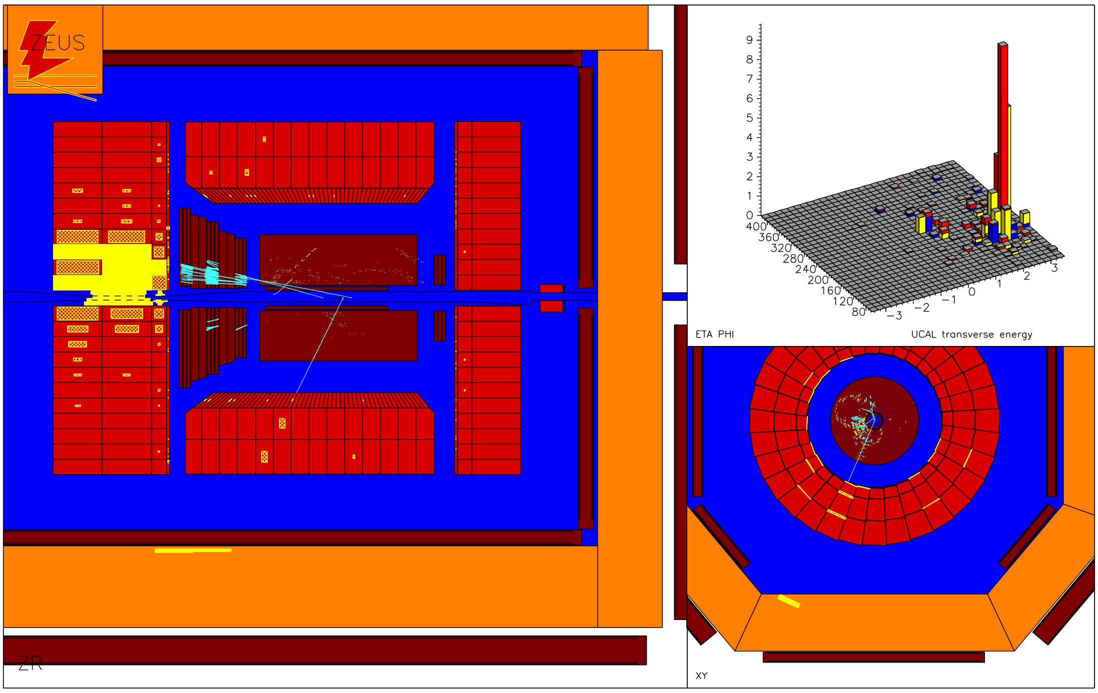

Figure 10: *The ZEUS muon event from 2000 which passed the $P_T^X > 25$ GeV cut.*

vertex. Here the quark can be generally u or c. At LEP, the limits come from a single-top search $e^+e^- \to tq$ and the TeVatron limits are from a rare top decay search $t \to q\gamma, qZ$. Both processes can constrain the γ and Z couplings, and the limits apply to both u and c quarks since they are in the final state. At HERA, the contribution from Z-exchange in the t-channel is suppressed due to the large mass in the propagator, so the cross section is dominated by the photon coupling k_γ. Moreover, since the u quark dominates the parton distribution in the proton at large x, HERA is most sensitive to the $tu\gamma$ coupling. It can be seen that the HERA limits on $k_{tu\gamma}$ are more stringent than those from LEP and the TeVatron. Note that the cross section dependence on the top mass uncertainty (5 GeV) is about 20% at HERA [19], while it is larger at LEP where the available energy is close to the threshold.

8 Summary and prospects

During the "HERA 1" running, both H1 and ZEUS experiments collected about 110 pb^{-1} of e^+p and 15 pb^{-1} of e^-p data. Not all of the searches have finished

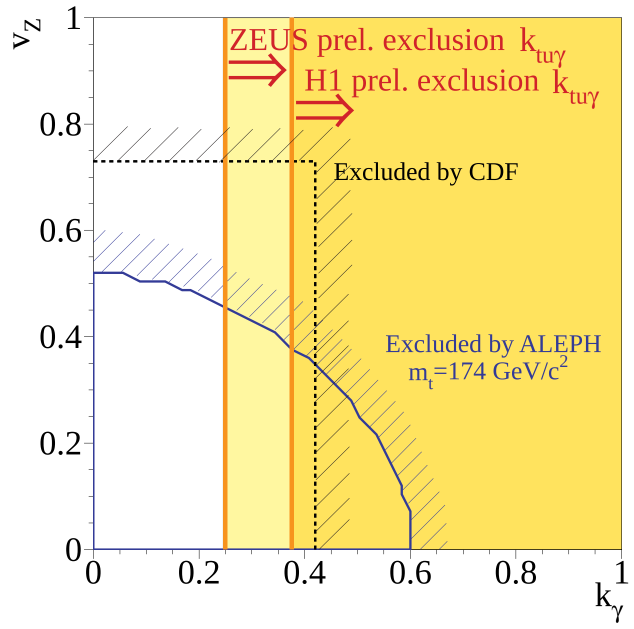

Figure 11: *Limits at 95% CL on FCNC magnetic coupling at the photon vertex, k_γ, and vector coupling at the Z vertex, v_Z, from LEP, TeVatron and HERA. The HERA limits apply only to $k_{tu\gamma}$.*

analyzing all of the data yet, but so far no evidence for new physics has been observed. Therefore, new constraints on various physics have been derived: leptoquarks, squarks in R-parity violating SUSY, $eeqq$ contact interactions, large extra dimensions, quark radius, lepton flavor violation and excited fermions. Limits are comparable and largely complementary to those obtained in searches at LEP or the TeVatron. The excess of isolated leptons in the H1 data is intriguing, although the ZEUS results from the total data sample are consistent with SM expectations. Limits on single-top production yield the most stringent constraint on the FCNC coupling at the $tu\gamma$ vertex.

HERA and both experiments have been performing shutdown work since September 2000 for the luminosity upgrade. New focusing magnets are installed very close to the interaction point, even inside the detectors. The new optics, together with a moderate increase in beam currents, will bring a five-fold increase in the instantaneous luminosity compared to the year 2000 running. In addition the detectors will be upgraded; for example, ZEUS will have a micro-vertex detector for

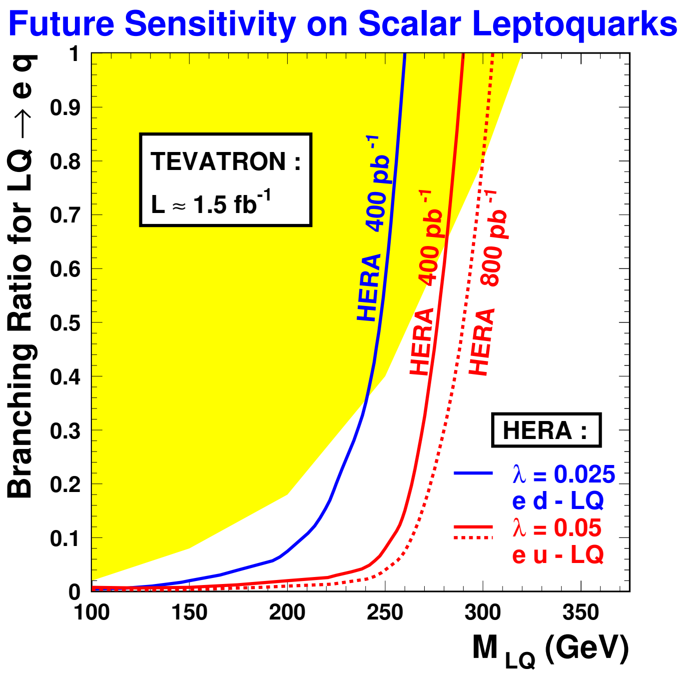

Figure 12: *Future prospects for scalar LQ sensitivity for TeVatron Run II (1.5 fb^{-1}) and HERA 2 (three different cases of coupling, LQ species and luminosity). Regions to the left of the curves are excluded.*

the first time. From summer 2001, the machine will restart and physics running is scheduled from December. In the five-year program of "HERA 2" running, approximately 1 fb^{-1} of data are expected per experiment. Another notable feature of the new running is that the longitudinal polarization of the electron/positron beam will be available by default to the collider experiments.

In these five years, HERA 2 and TeVatron Run II will be the only energy-frontier machines in operation. They will compete in many physics scenarios. For example, leptoquark (or squark) sensitivity is illustrated in Fig. 12 [20]. If the Yukawa coupling λ is within the sensitivity of HERA, and if HERA 2 quickly starts up with high-luminosity running, there is a chance for discovery with 10 times more data to come. Otherwise, for the case of leptoquarks decaying 100% to eq, with 1-2 fb^{-1} of Run II data the TeVatron experiments can close the discovery window for direct observation at HERA since the λ-independent mass limit will exceed the HERA kinematic limit. However, there are cases where HERA has still potential not covered by Run II; as indicated in the figure, in the case of leptoquarks with a small branching ratio to eq, HERA's sensitivity exceeds that of Run II even for fairly small Yukawa coupling. Also there are some models not probed extensively at the TeVatron such as excited leptons. Therefore, the two colliders will continue to be competitive and complementary during the coming years before the start of LHC, in the hunt for possible excitement.

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