DEUTSCHES ELEKTRONEN-SYNCHROTRON

DESY 93-096
July 1993

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ISSN 0418-9833

NOTKESTRASSE 85 - 22603 HAMBURG

DESY 93-096
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ISSN 0418-9833

SEARCHES FOR NEW PARTICLES AT HERA

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ABSTRACT

Some of the physics motivation for new particles, their main signatures and most importantly, the prospects for finding them at HERA will be reviewed. For each species of interest, a HERA discovery window will be presented, based on a generic reference luminosity of $100 - 200\ \mathrm{pb}^{-1}$. The experimental constraints from LEP as well as the present and near future ones from CDF are taken into account. The first HERA results on searches for leptoquarks and excited leptons are also included.

1. Setting the Stage

From the wealth of precision measurements at LEP we know that altogether, the Standard Model (SM) is in excellent shape[1]! Via radiative corrections, there are many *indirect* constraints on the *sum* of top, Higgs and possible new physics contributions. From the LEP experiments though, it has become clearer than ever before that the motivation for "New Physics" at some scale $\Lambda \geq O(\mathrm{TeV})$ is *entirely* theoretical in nature.

The main theoretical reasons for contemplating new physics beyond the Standard Model are well known by now.[2] First of all, there is the basic quest for the origin of mass and spontaneous electroweak symmetry breaking, respectively, residing in the Higgs sector with its many free parameters. For it, the observed enormous mass hierarchy and the socalled finetuning problem, the Standard Model has no answers to offer. Similarly, the origin of flavours and the striking generation pattern remain mysterious.

Traditionally, there are two main routes leading beyond the Standard Model, but there are no satisfactory realizations as yet.

- *The strong coupling route*: Here, one imagines the existence of a further strong gauge force (Technicolor,...), giving rise to a *dynamical* breaking of symmetries including the electroweak one. Possibly it also holds together constituents of quarks and leptons. The generic role model is QCD. The new physics scale is relatively low, $\Lambda \simeq O(\mathrm{TeV})$, such that no finetuning of the Higgs mass parameter arises.

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[*] Invited talk at the "Symposium in Honor of Tetsuro Kobayashi's 63rd Birthday", Tokyo, March 19th 1993. To be published in the "Festschrift".

- *The weak coupling route*: Here, supersymmetry (SUSY) is a key building block in order to keep the finetuning problem under control, as well as extended or grand unified gauge theories. At the end of that road, there may be (super)strings...along with the "theory of everything".

Irrespective of which of the two routes is preferred by Nature, there will be one conspicous common signature:

The occurence of a wealth of new particles with masses below $O(\mathrm{TeV})$!

On the 'strong coupling' side, on may expect relatively light (pseudo) Goldstone bosons associated with a dynamical breaking of global symmetries by the new, hypothetical strong gauge force. Spectacular candidates for HERA could well be leptoquarks. In the framework of compositeness, one expects excited leptons (l^*) and quarks (q^*) or even further exotics like leptogluons, which are leptons transforming like gluons in color space.

On the the 'weak coupling' side, there are first of all the long awaited SUSY partners. Extended or grand unified gauge theories require the existence of new fermions and gauge bosons (to realize the extended symmetries). Leptoquarks do also occur in such scenarios.

The plan of this paper is as follows. For each new particle species of interest, I shall summarize in the following sections some further theoretical background, the main experimental signatures and in particular, the discovery prospects at HERA. In each case, a "HERA discovery window" will be presented, based on a generic reference luminosity of $100 - 200\ \mathrm{pb}^{-1}$. The experimental constraints from LEP as well as the present and near future ones from the Tevatron are taken into account. The latest HERA results from H1 and ZEUS on searches for leptoquarks and excited leptons at a present sensitivity of $\int \mathcal{L} dt \approx 25\ \mathrm{nb}^{-1}$ are also reported.

Sects. 2 and 3 are devoted to leptoquarks and new fermions, respectively. In Sect. 4, I shall discuss three quite different scenarios for possible manifestations of SUSY partners at HERA. The first one refers to the minimal supersymmetric standard model (MSSM), next I consider the interesting possibility of a light scalar top and finally, I shall review the implications of broken R parity for HERA. In Sect. 5, I report on a model independent analysis of possible effects of virtual new particle exchanges in the contact interaction limit. Due to its generality, this approach nicely complements and extends the direct searches for new particles at HERA.

Brief conclusions on the discovery prospects for each new particle species may be found at the end of the corresponding sections.

2. Leptoquarks

2.1. Motivation and Classification

Leptoquarks are color triplet bosons with spins $J = 0, 1, \cdots$, non-zero baryon and lepton number (B, L) and fractional electric charge, coupling to quark–(anti)lepton pairs. Clearly, an $e^{\mp}p$ collider like HERA represents an ideal machine for hunting them, since they give rise to dramatic formation peaks in the $e^{\mp}q$ (sub) process at a fixed value of $x = m_{\mathrm{LQ}}^2/s$. A more detailed review on leptoquarks may e. g. be found in Ref. .[3-5] Let me summarize here some essential aspects.

Table 1. Scalar (S) and vector (V) leptoquarks with their weak isospin 0, 1/2, 1 attached as suffix to the name; their $SU(3) \times SU(2) \times U(1)$-invariant couplings to lepton-quark pairs, where ℓ_L and q_L denote the left-handed lepton and quark doublets ; their electric charges Q and their decay channels with respective couplings. The leptoquarks in the upper (lower) block are color triplets (antitriplets) and have fermion number F= 2 (0). From Ref.[3]

leptoquark name	coupling to left-handed leptons	coupling to right-handed leptons	Q	decay channels (coupling)
S_0	$\lambda_{L\,S_0}\,\bar{q}^c_L\,i\tau_2\,\ell_L\,S_0^\dagger$	$\lambda_{R\,S_0}\,\bar{u}^c_R\,e_R\,S_0^\dagger$	$-\frac{1}{3}$	$e_L u$ (λ_L) $\nu_L d$ $(-\lambda_L)$ $e_R u$ (λ_R)
$\tilde{S}_0$		$\lambda_{R\,\tilde{S}_0}\,\bar{d}^c_R\,e_R\,\tilde{S}_0^\dagger$	$-\frac{4}{3}$	$e_R d$ (λ_R)
S_1	$\lambda_{L\,S_1}\,\bar{q}^c_L\,i\tau_2\vec{\tau}\,\ell_L\,S_1^\dagger$		$+\frac{2}{3}$ $-\frac{1}{3}$ $-\frac{4}{3}$	$\nu_L u$ $(\sqrt{2}\lambda_L)$ $\nu_L d$ $(-\lambda_L)$ $e_L u$ $(-\lambda_L)$ $e_L d$ $(-\sqrt{2}\lambda_L)$
$V_{1/2}$	$\lambda_{L\,V_{1/2}}\,\bar{d}^c_R\,\gamma^\mu\,\ell_L\,V_{1/2\,\mu}^\dagger$	$\lambda_{R\,V_{1/2}}\,\bar{q}^c_L\,\gamma^\mu\,e_R\,V_{1/2\,\mu}^\dagger$	$-\frac{1}{3}$ $-\frac{4}{3}$	$\nu_L d$ (λ_L) $e_R u$ (λ_R) $e_L d$ (λ_L) $e_R d$ (λ_R)
$\tilde{V}_{1/2}$	$\lambda_{L\,\tilde{V}_{1/2}}\,\bar{u}^c_R\,\gamma^\mu\,\ell_L\,\tilde{V}_{1/2\,\mu}^\dagger$		$+\frac{2}{3}$ $-\frac{1}{3}$	$\nu_L u$ (λ_L) $e_L u$ (λ_L)
$S_{1/2}$	$\lambda_{L\,S_{1/2}}\,\bar{u}_R\,\ell_L\,S_{1/2}^\dagger$	$\lambda_{R\,S_{1/2}}\,\bar{q}_L\,i\tau_2\,e_R\,S_{1/2}^\dagger$	$-\frac{2}{3}$ $-\frac{5}{3}$	$\nu_L \bar{u}$ (λ_L) $e_R \bar{d}$ $(-\lambda_R)$ $e_L \bar{u}$ (λ_L) $e_R \bar{u}$ (λ_R)
$\tilde{S}_{1/2}$	$\lambda_{L\,\tilde{S}_{1/2}}\,\bar{d}_R\,\ell_L\,\tilde{S}_{1/2}^\dagger$		$+\frac{1}{3}$ $-\frac{2}{3}$	$\nu_L \bar{d}$ (λ_L) $e_L \bar{d}$ (λ_L)
V_0	$\lambda_{L\,V_0}\,\bar{q}_L\,\gamma^\mu\,\ell_L\,V_{0\,\mu}^\dagger$	$\lambda_{R\,V_0}\,\bar{d}_R\,\gamma^\mu\,e_R\,V_{0\,\mu}^\dagger$	$-\frac{2}{3}$	$\nu_L \bar{u}$ (λ_L) $e_L \bar{d}$ (λ_L) $e_R \bar{d}$ (λ_R)
$\tilde{V}_0$		$\lambda_{R\,\tilde{V}_0}\,\bar{u}_R\,\gamma^\mu\,e_R\,\tilde{V}_{0\,\mu}^\dagger$	$-\frac{5}{3}$	$e_R \bar{u}$ (λ_R)
V_1	$\lambda_{L\,V_1}\,\bar{q}_L\,\vec{\tau}\gamma^\mu\,\ell_L\,V_{1\,\mu}^\dagger$		$+\frac{1}{3}$ $-\frac{2}{3}$ $-\frac{5}{3}$	$\nu_L \bar{d}$ $(\sqrt{2}\lambda_L)$ $\nu_L \bar{u}$ (λ_L) $e_L \bar{d}$ $(-\lambda_L)$ $e_L \bar{u}$ $(\sqrt{2}\lambda_L)$

Leptoquarks tend to occur in almost any theoretical scheme beyond the Standard Model, where quarks and leptons appear on the same footing, be it as members of higher symmetry multiplets or by sharing joint constituents. Typical examples are grand unified theories (GUT's), notably superstring inspired E_6 models,[6] Technicolor schemes[2] and quark-lepton compositeness.[7,8]

The standard leptoquark in minimal GUT and superstring inspired E_6 versions[6] is a scalar isosinglet leptoquark with electric charge $Q = -1/3$ (termed S_0 in Table 1).

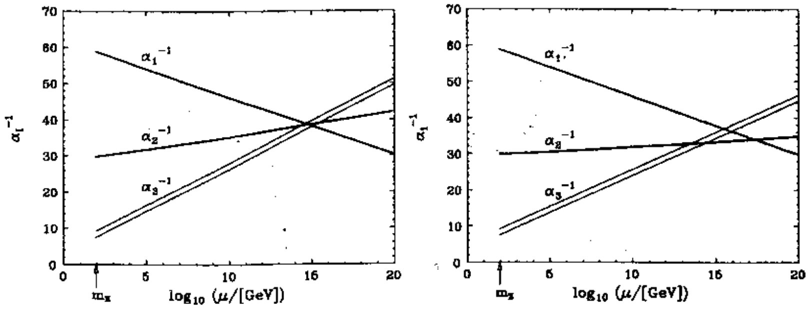


Fig. 1. Impact of a pair of $\tilde{S}_{1/2}$ leptoquarks in Table 1 on the evolution of the three (inverse) gauge couplings.[9] They lead to perfect unification at the GUT scale (left), unlike the minimal $SU(5)$ theory (right).

Another species (termed $\tilde{S}_{1/2}$ in Table 1), might deserve special attention. It has recently been noted in Ref.[9] that it may 'save' $SU(5)$ grand unification without invoking SUSY.[10] This "$SU(5)$ saver" leptoquark is a scalar isodoublet and was introduced in Ref.[9] as a member of a $\underline{10}$ plet in the scalar sector of $SU(5)$. Despite leading to a non-minimal extension of $SU(5)$, it achieves an appealing scalar-fermion symmetry in the representation content of the model. The only allowed (first generation) Yukawa couplings of $\tilde{S}_{1/2}$ are to $e_L \bar{d}_R$ and $\nu_L \bar{d}_R$, which do not cause proton decay. Most importantly, the inclusion of a pair of $\tilde{S}_{1/2}$ leptoquarks into the renormalization group evolution of the SM gauge couplings leads to perfect unification at the GUT scale (Fig. 1 left), unlike the minimal $SU(5)$ theory (Fig. 1 right). The resulting proton life time is marginally consistent with experiment. The mass of this leptoquark is not bounded by any of the stringent low-energy constraints (see below) and thus could well be within the reach of HERA.

Unfortunately, not much can in general be said, about the expected mass range of leptoquarks. Only in case that leptoquarks are pseudo-Goldstone bosons, there is a qualitative estimate of their mass due to colour interactions, which may deserve some confidence.[11,8]

$$m_{LQ} \simeq O(1) \cdot \sqrt{\frac{\alpha_S(\Lambda)}{\pi}}\,\Lambda, \tag{1}$$

such that with $\Lambda \simeq 1$ TeV and the color gauge coupling $\alpha_S(\Lambda) \simeq 0.1$, a Goldstone-leptoquark might well fit into the range accessible at HERA. An analogous formula successfully predicts the electromagnetic mass (difference) of the pseudo-Goldstone boson of QCD, the (charged) pion.[11]

An exhaustive classification of leptoquarks, whose interactions are B and L conserving, $SU(3)_{\rm color}\times SU(2)_L\times U(1)_Y$ symmetric and 'renormalizable', i. e. of mass dimension ≤ 4, has been performed in Ref.[12] With these restrictions, there are altogether ten possible species, which are displayed in Table 1 together with their couplings labeled by the lepton chirality, electric charges and decay channels. I have adopted the spectroscopic "Aachen" notation[5] to label the various leptoquarks.

2.2. Low-energy Constraints

The experimental limits on rare decays and $(g-2)_e$ imply, besides the absence of generation changing $q-l$ couplings, in particular their *chiral* 'protection',[13,14] i.e.

$$\lambda_L \cdot \lambda_R \approx 0 \quad \text{for } S_0,\, S_{1/2},\, V_0,\, V_{1/2}. \tag{2}$$

A second constraint results from $q-l$ universality[13] ($G_F^{\mu\text{ decay}} = G_F^{\beta\text{ decay}}$) and affects certain left-handed leptoquark couplings only

$$\frac{m_{LQ}}{\lambda_L} > 1.7\ \text{TeV} \quad \text{for } S_0,\, S_1,\, V_0,\, V_1. \tag{3}$$

2.3. HERA Discovery Window

At e^+e^- colliders, leptoquarks may be produced predominantly in pairs[8,15] if $m_{LQ} < \sqrt{s}/2$ and singly in the mass range, $\sqrt{s}/2 < m_{LQ} < \sqrt{s}$. Notably at LEP I, the pair production cross section is largely determined by Z^0 and γ gauge boson exchange in the s channel, involving just the electroweak gauge couplings, the weak $SU(2)$ group structure (Z^0) and the electric charge (γ) of the leptoquark. A typically small contribution to pair production via quark exchange in the t channel as well as the single production ($d\sigma \propto O(\alpha^2\lambda^2/4\pi)$), depend on the Yukawa couplings λ of the leptoquark.

At $p\bar{p}$ colliders, leptoquark production[16] proceeds via $q\bar{q}$ fusion and dominantly, gg fusion, such that here, the strength of leptoquark pair production depends largely on α_s and the colour representation of the leptoquark and not on its electroweak properties. In addition, leptoquarks may be singly produced via qg fusion. The single production cross section again involves the Yukawa coupling λ, $d\sigma \propto O(\alpha_s\lambda^2/4\pi)$, and is much smaller, notably due to the steeply falling gluon spectrum.

The obtainable mass limits from $p\bar{p}$ colliders, in addition depend sensitively on the decay branching ratio of the leptoquark into a charged lepton (and a quark).

At HERA, there is the unique possibility to observe leptoquarks as dramatic (narrow) formation peaks[12] in the $e^{\mp}q$ subprocess at a fixed value of $x = m_{LQ}^2/s$. In contrast to e^+e^- and $p\bar{p}$ colliders, the dominant production cross section does not depend on SM gauge couplings, but exclusively on the Yukawa couplings λ.

The spin of the leptoquark determines the y ($= Q^2/xs$) dependence of the cross sections. Scalar leptoquarks lead to a flat y distribution, while vector leptoquarks yield a profile $\sim (1-y)^2$. By placing clever cuts in y, the analyzing power for different leptoquark spins at HERA can therefore be considerably enhanced.[4]

Since the topologies of leptoquark (decay) events and of deep inelastic scattering (DIS) events are indistinguishable and the natural width of leptoquarks is very small, good control over the DIS background and an optimal reconstruction of the leptoquark mass is of highest importance at HERA.

The present and near future experimental situation with respect to leptoquark searches at LEP, hadron colliders and at HERA is summarized in the 'HERA Discovery Window for Leptoquarks", Table 2.

Table 2. HERA discovery window for leptoquarks in comparison with existing and near future searches at e^+e^- and hadron colliders.

HERA Discovery Window for Leptoquarks

	m_{LQ} [GeV]		Remarks
LEP[17,18]	> 44.4		$J=0$ only
UA2[19]	> 76 > 67	if Br(eq)= $\left\{\begin{array}{l}1\\ \frac{1}{2}\end{array}\right.$	$J=0$ only independent of λ
CDF[20,21] ('92) 4.4 pb^{-1}	> 116 ≥ 80	if Br(eq)= $\left\{\begin{array}{l}1\\ \frac{1}{2}\end{array}\right.$	$J=0$ only independent of λ
HERA[22,23] ('92) $\simeq 25$ nb^{-1}	$> 100 - 190$	for $\lambda = e$	first data! see Figs. 2, 3
HERA[4,24] 100 pb^{-1}	$> 150 - 250$ ≥ 300	for $\lambda = 0.1e$ for $\lambda = e$	$J=0,\,1$, selective! see Fig. 4
CDF[21] ($\geq$'93) $\simeq 25$ pb^{-1}	> 170	if Br(eq)= 1	independent of λ

In Figs. 2 and 3 the encouraging mass (rejection) limits from first leptoquark searches by the H1 and ZEUS collaborations,[22,23] respectively, are displayed. Even at the present sensitivity of only $\int \mathcal{L}dt \simeq 25$ nb^{-1}, and Yukawa couplings $\lambda = e$, leptoquark masses as high as 100 – 190 GeV (depending on type) can already be excluded! Clearly for e^- (e^+) beams, by far the best limits are for leptoquarks with $F = 2(0)$ since they involve the dominant valence quark distributions in the proton, rather than antiquarks from the sea.

The projected exclusion potential for leptoquarks at HERA is detailed in Fig. 4 from a simulation at $\int \mathcal{L}dt = 100$ pb^{-1} in Ref. .[4] Apparently, even for $\lambda = 0.1e$, HERA

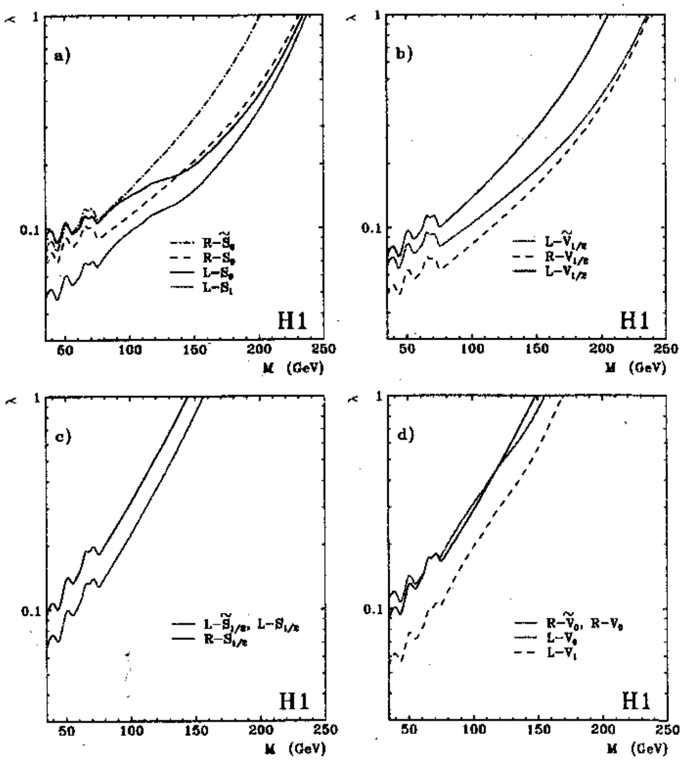


Fig. 2. Rejection limits at 95% CL from H1[22] for the coupling $\lambda_{L,R}$ as a function of mass for scalar and vector leptoquarks with fermion number F=2 (a), (b) and F=0 (c), (d). The regions above the curves are excluded. The limits on λ_L for S_0, S_1, V_0 and V_1 combine charged and neutral decays.

will be sensitive to leptoquark masses as high as $150 - 250$ GeV[4,24]! The low energy constraints (3) on the leptoquark mass and couplings from $q - l$ universality will be surpassed by far, where applicable.

In summary: Hunting for leptoquarks represents a great opportunity for HERA, where the largest range in couplings and masses may be explored in the near future. e^+e^-, $p\bar{p}$ and ep colliders exhibit– via the different, dominant production mechanisms– a *complementary* sensitivity to various properties of leptoquarks, like electric charge, weak $SU(2)$ and color assignments and their Yukawa couplings.

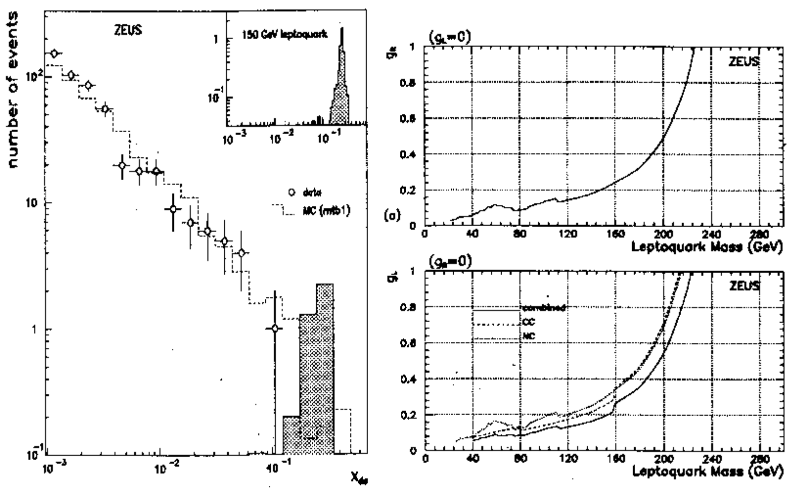


Fig. 3. Results from a search for leptoquarks by ZEUS[23];
left: Event distribution in x, compared to the Monte Carlo prediction (open dashed histogram) and the expected signal from a scalar leptoquark of mass $m_{LQ} = 150$ GeV with electroweak coupling, $\lambda = e$;
right above (below): The 95% confidence upper limits on the couplings of the leptoquark S_0 for right (left) handed coupling, $\lambda = g_R(g_L)$. In the former case, only the neutral current data contribute; in the latter case, limits are shown from neutral current data (dotted),from charged current data (dashed) and from a combination of both (solid).

3. New Fermions

3.1. *Motivation and Classification*

The list of new fermion candidates is long and there is considerable motivation for them to exist, even if we ignore Supersymmetry for the time being:

(Heavy) Majorana neutrinos N :

Right-handed neutrinos could even exist in a SM framework, where they may help explaining nonvanishing, but naturally small masses of the known neutrinos via the so-called "see saw" mechanism.[25] Let me briefly recall the basic idea.[26] Since right-handed neutrinos ν_R are singlets with respect to the SM gauge group, one may add to the SM Lagrangian both a Yukawa interaction term producing a Dirac neutrino mass via spontaneous symmetry breaking and a Majorana mass term involving ν_R

$$\mathcal{L}_\nu^{mass} = -(\bar{l}\phi)g_\nu\nu_R - \frac{1}{2}\bar{\nu}_R M \nu_R^c + h.c. \tag{4}$$

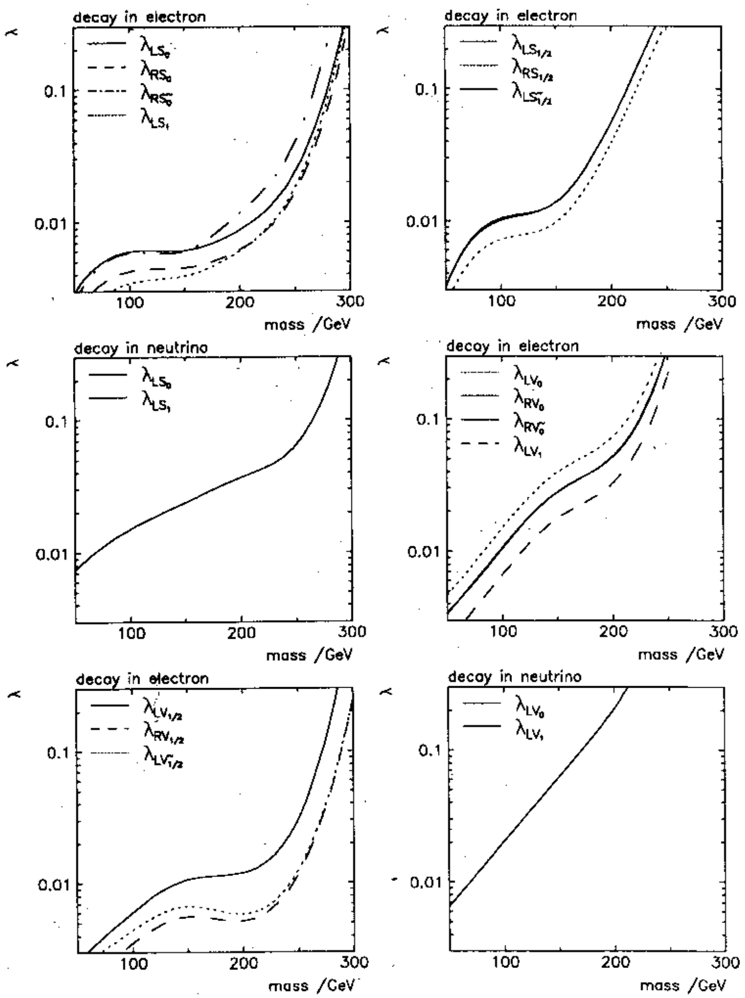


Fig. 4. Leptoquark exclusion limits[4] for all couplings versus mass at 95% CL to be expected at HERA for $\int \mathcal{L}dt = 100$ pb^{-1} The figures on the left (right) refer to scalar and vector leptoquarks with fermion number F=2(0). The regions above the curves are excluded.

Here, l = (ν_L, e_L^-) is the lepton doublet, ϕ the doublet of Higgs fields and $\nu_R^c = C\bar{\nu}_R^T$ with the charge conjugation matrix C. $m_D = vg_\nu$ and $M = M^T$ are 3 x 3 matrices in generation space of Dirac and Majorana masses, respectively, and $v =<\phi>= 174$ GeV. The Majorana mass matrix M can always be chosen real and diagonal. For a proper choice of the fields ν_L, the mass eigenstates are found by diagonalization, which after expanding in the small mixing quantity

$$\xi = (m_D M^{-1}), \tag{5}$$

reads approximately

$$\begin{aligned} m_N &= M + O(\frac{1}{M}) \text{ (heavy)}; \\ m_\nu &= -m_D \frac{1}{M} m_D^T + O(\frac{1}{M^3}) \text{ (light)}, \end{aligned} \tag{6}$$

To leading order in $1/M$, m_N and m_ν are both diagonal and real. It is intriguing that heavy Majorana masses M of the order of v are sufficient to explain the smallness of the light neutrino masses in accordance with the experimental upper bounds[27] $m_{\nu_e} < 8$ eV, $m_{\nu_\mu} < 270$ keV and $m_{\nu_\tau} < 35$ MeV.

Right-handed neutrinos are predicted in most extensions of the standard model, notably in extended/unified gauge theories like $SO(10)$ or E_6 or left right symmetric scenarios with gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, which is a subgroup of $SO(10)$ or E_6.

Local symmetries are often considered to be preferrable to global ones. In the SM there is one more conserved global symmetry (per generation i=1,..,3), namely $U(1)_{B-L_i}$, which may be gauged if (per generation) a right-handed neutrino is added to the spectrum of known fermions. The reason is that the $(B - L_i)$ assignments of the fermions then become left-right symmetric, such that both gauge and gravitational anomalies cancel. (Baryon number (B) and Lepton number (L_i) separately are broken due to an Adler-Bell Jackiw anomaly in the presence of $SU(2)_L$ currents). This scenario is realized in $SO(10)$ grand unification, for example, which is one of the simplest and most economic extensions of the SM. Here, B-L plays the role of a spontaneously broken local symmetry, with neutrinos acquiring masses proportional to the scale of B-L breaking and exact global symmetries are absent (for one generation). It is also important to realize that in view of these arguments, the possible existence of additional Z' *gauge* bosons requires in general the existence of new fermions of masses[28] $\propto m_{Z'}$, since the SM fermion content only admits $U(1)_Y$ to be gauged. A general feature of theories with massive Majorana neutrinos is the violation of the lepton number symmetry, which may have characteristic observable consequences to be discussed further below.

27-plet of E_6 fermions:

Within the framework of extended/unified gauge theories further new fermions are usually required, since the known fermions only fill part of the representations of the assumed higher symmetry group.

In case of the (anomaly free) unifying group $SO(10)$, the smallest (complex) representation admitting chiral fermions has dimension 16 and hence in addition to the 15 known Weyl fermions in one q-l generation, only one right handed neutrino is needed in addition, as discussed above.

In recent years, much attention has also been devoted to Superstring motivated GUT's based on the exceptional group E_6. It has a 27-plet of fermions as its fundamental representation. Here, twelve new chiral fields are needed (per generation) to complete the representation. These are two weak $SU(2)_L$ doublets of heavy leptons, $(\nu_E, E)_{L,R}$, one being left handed, the other one right handed, two $SU(2)_L$ singlets of neutrinos N, N', which can be either of Dirac or Majorana type and two $SU(2)_L$ singlet quarks $D_{L,R}$ of charge -1/3.

Mirror Fermions:

Mirror fermions are fermions with the same representation content as the ordinary fermions, but flipped chirality. For instance right handed $SU(2)_L$ doublets or left handed $SU(2)_L$ singlets would be mirror fermions. They occur not only in extended/unified theories such as the E_6 GUT's above, but -remarkably- already in attempts to achieve a consistent lattice regularization[29] of the SM. The mirror doubling of the fermion spectrum in non-perturbative formulations of chiral gauge theories (like the SM) on the lattice, is not easy to avoid, as is well known from the Nielsen-Ninomiya theorem.[30] It might well turn out that the mirror partners remain in the physical spectrum in the continuum limit of lattice gauge theories.

Excited Fermions:

The existence of excitations of the known (groundstate) quarks and leptons would be one of the most typically expected signals of q-l substructure. However, at least naively, one might well expect the masses of such excited fermions to be of the order of the compositeness scale $\Lambda \geq O(1\text{TeV})$. Searches for excited leptons have a long history[31] and belong to the standard 'repertoire' at particle accelerators.

Among possible exited fermions, excited leptons L^* are of most direct relevance for HERA. Their transition to ordinary leptons and a gauge boson $V = \gamma,\ Z,\ W$, is described[32] by a magnetic interaction of dimension 5, involving a compositeness scale Λ and in general two dimensionless coupling parameters c_{VL^*l}, d_{VL^*l} per gauge boson V. Their ratio characterizes the "chiral mixture" of L^*_L and L^*_R participating in the de-excitation to ordinary leptons l.

$$\mathcal{L}^{L*}_{\text{eff}} = \frac{e}{\Lambda} \sum_{V=\gamma,Z,W^\pm} \bar{L}^* \sigma^{\mu\nu} (c_{VL^*l} - d_{VL^*l}\gamma_5)\, l\, \partial_\mu V_\nu + h.c. \tag{7}$$

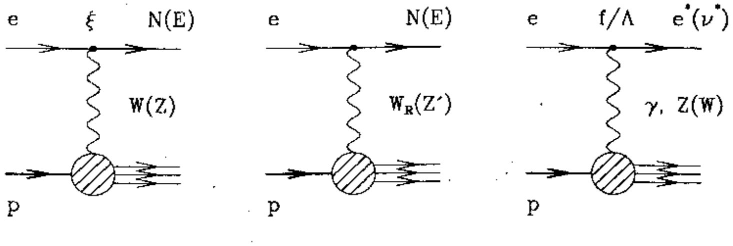
The interaction (7) should, in fact, respect a chiral symmetry,[32] in order to prevent the light leptons from radiatively acquiring a large anomalous magnetic moment, implying

$$| c_{\gamma L^* l} | = | d_{\gamma L^* l} | . \tag{8}$$

A strong reduction of parameters is achieved with the popular assumption[32] that the excited fermions occur as weak $SU(2)$ doublets like the other fermions. Moreover, it is natural to assume that their mass generation arises prior to $SU(2)_L \times U(1)_Y$ breaking and accordingly, their couplings to the gauge fields are taken vectorlike.

3.2. Production Mechanisms

The new lepton species introduced in the previous subsection can all be singly produced at HERA. As is illustrated in Fig. 5, the production may either proceed via the exchange of known gauge bosons γ, Z, $W^\mp$ or via new ones, like $W^\mp_R$ or Z'. In the former case, Majorana neutrinos, other E_6 leptons and mirror leptons couple to the initial electrons via a small mixing parameter ξ, (c. f. Fig. 5a and Eq. (5)), the size of which is most strongly constrained at LEP[33]



a) b) c)

Fig. 5. Mechanisms for single production of new fermions at HERA

$$\xi^2 \leq 0.01. \tag{9}$$

The production rate at HERA is correspondingly small

$$\sigma \propto \xi^2. \tag{10}$$

In case of excited lepton production via the exchange of known gauge bosons V, (c. f. Fig. 5c), the suppression of the rate results from the small quantity $c(d)_{VL^*l}/\Lambda$ in (7),

$$\sigma \propto \frac{| c_{VL^*l} |^2 + | d_{VL^*l} |^2}{\Lambda^2}. \tag{11}$$

Finally, in case of new gauge boson exchange, like W_R, (c. f. Fig. 5b), there is no mixing involved. Here, the suppression of the production rate comes from the known restictions on the mass of the exchanged W_R boson. LEP bounds on $m_{Z'} > 800$ GeV and the vector boson mass formulae in the L-R symmetric $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ extension of the SM may be combined to give,[35]

$$m_{W_R} > 450 GeV, \tag{12}$$

such that

$$\sigma \propto \left(\frac{m_W}{m_{W_R}}\right)^4, \tag{13}$$

is also very small.

3.3. *Decays and Signature*

The decays and the signatures of the produced leptons depend strongly on the species considered. For reasons of space and size of expected cross sections, let me confine the discussion from now on to Majorana neutrinos and excited leptons. The cross sections for other exotic leptons are even smaller.

(Heavy) Majorana Neutrinos:

Let me specialize on the (most promising case) that Majorana neutrinos are coupled to ordinary charged and neutral currents. In this case, they will decay into either $\nu_l Z^0$, l^+W^- or l^-W^+, again involving the small mixing ξ (Eq. (5)). The V bosons in the final states may be considered on shell since existing mass limits from LEP restrict $m_N > m_Z$. One finds[34]

$$\begin{aligned} \Gamma(N \to l^\pm W^\mp) &= \frac{|(V\xi)_{lN}|^2 G_F}{8\sqrt{2}\pi m_N^3}(m_N^2 + 2m_W^2)(m_N^2 - m_W^2)^2 \\ \Gamma(N \to \nu_l Z) &= \frac{|\xi_{\nu_l N}|^2 G_F}{8\sqrt{2}\pi m_N^3}(m_N^2 + 2m_Z^2)(m_N^2 - m_Z^2)^2, \end{aligned} \tag{14}$$

where G_F is the Fermi constant. Assuming the Kobayashi-Matrix type matrix V for the lepton sector to be diagonal, so that $|(V\xi)_{lN}| = |\xi_{\nu_l N}|$, all three branching ratios equal 1/3 at large Majorana neutrino masses. However, due to the $m_Z - m_W$ mass difference, $\sum_l Br(N \to l^\pm W^\mp)$ is significantly larger than 1/3 for m_N not too far above $m_{W,Z}$, which improves the resulting mass limits somewhat.[34]

A crucial feature is, of course, the lepton number violation, which becomes apparent in the equality of the branching ratio into leptons with positive and negative charge, characteristic for the decay of a Majorana neutrino.[26] Since –unlike LEP– the lepton number of the initial ep state at HERA is nonzero, one may look for a L violating final state

$$e^- + p \to e^+ + W^- + X \to e^+ + 2jets + X \tag{15}$$

as a characteristic signature for the production and decay of a Majorana neutrino, which has much less background than the corresponding L conserving channel with a negatively charged lepton in the final state. In the latter case the background is overwhelming and consists of normal deep inelastic events, heavy flavour production via boson gluon fusion and W/Z production.[34]

Excited Leptons:

According to the effective Lagrangian (7) excited leptons L^* decay into a lepton and a gauge boson $V = \gamma,\ Z^0,\ W$. For L^* masses below 500 GeV their width is expected to be very narrow, i. e. below 1 GeV. At HERA not only the decay modes with a photon in the final state, but also with W and Z bosons may be investigated for the first time, due to the high centre of mass energy available for direct L^* production according to Fig. 5c.

3.4. *The HERA Discovery Window*

The present and near future experimental situation with respect to Majorana neutrino and excited lepton searches at LEP, (hadron colliders) and at HERA is summarized in the "HERA Discovery Window for new Leptons", Table 3.

Table 3. HERA discovery window for new leptons in comparison with searches at e^+e^- and hadron colliders.

HERA Discovery Window for New Leptons

	m_{N} [GeV]	mixing ξ^2	$m_{\mathrm{W_R}}$ [GeV]	m_{e^*} (m_{ν^*}) [GeV]
LEP[33,18]	> 82	0.01		> 84 (86) $c_{Zl^*l}/\Lambda = 0.5/\mathrm{TeV}$
CDF[21] ('92) $\simeq 4.4\ \mathrm{pb}^{-1}$			> 520 if $m_N < 15$ GeV	
HERA[22,37] ('92) $\simeq 25\ \mathrm{nb}^{-1}$				first data! see Figs. 6, 7
HERA[34–36] 200 pb^{-1}	> 160 > 120	0.01	450	> 200 (> 150) $c_{\gamma e^* e}/\Lambda = 0.5/\mathrm{TeV}$

The discovery potential for Majorana neutrinos at HERA via normal charged and neutral currents has been most recently studied by means of a detailed Monte Carlo simulation,[34] while the entry for the Majorana neutrino mass limit in case of right handed currents, with $m_{W_R} = 450$ GeV, is from Ref. .[35] Since the expected cross sections are quite small (< 100 fb for $m_N = 100$ GeV) an integrated luminosity of 200 pb^{-1} has been assumed.

The results on first searches for excited leptons from ZEUS[37] and H1[22] are displayed in Figs. 6, 7.

In summary: Searches for new leptons are certainly worthwhile at HERA. The motivations for the existence of new fermions with masses below ~ 1 TeV are sound. However sufficient luminosity is crucial for their possible discovery! A HERA upgrade would increase the discovery potential for new leptons considerably.

4. SUSY Partners

Supersymmetry (SUSY) offers an elegant and promising way of overcoming some of the basic difficulties of the SM. In particular, it can stabilize the SM Higgs sector, provided the masses of the superpartners are lighter than ~ 1 TeV.

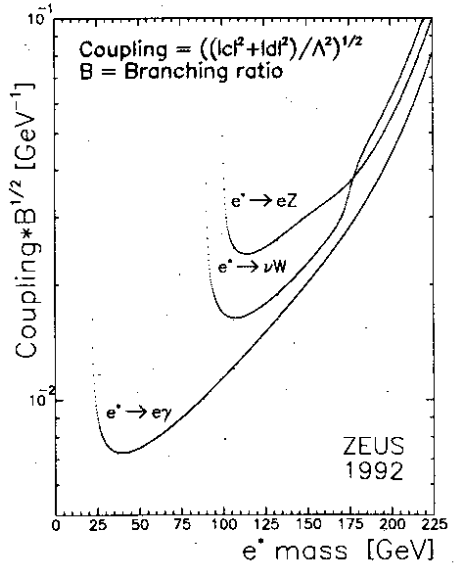


Fig. 6. e^* rejection limits at 95 % CL from ZEUS[37] for $e\gamma$, eZ and νW final states. The notations are explained in the text.

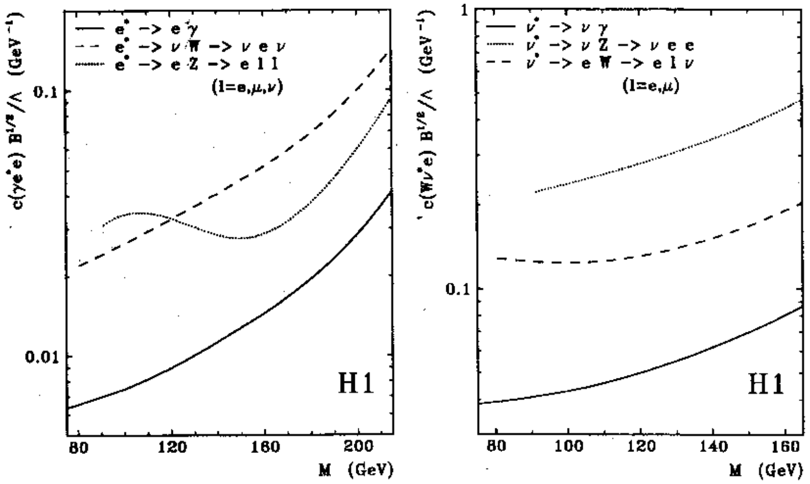


Fig. 7. e^* and ν^* rejection limits at 95 % CL from H1.[22] Regions above the curves are excluded. The notations are explained in the text.

4.1. *Minimal Supersymmetric Standard Model*

Phenomenological implications of SUSY have been most thoroughly analysed in the minimal supersymmetric standard model[38] (MSSM), which involves the minimal number of particles and the minimal superpotential consistent with the SM. It has received much renewed attention, recently, since unlike ordinary $SU(5)$ GUT, the three gauge couplings (and the proton life time) are consistent within the high precision of LEP data, with grand unification of the MSSM.[10]

The MSSM has a discrete, multiplicative symmetry, the so-called R parity

$$R = (-1)^{2S+3B+L}, \tag{16}$$

where S, B and L are the spin, the baryon and the lepton number, respectively. Since sparticles have $R = -1$, while $R = +1$ for ordinary matter, sparticles are always pair produced and the lightest sparticle (LSP) is stable. The LSP is usually assumed to be the lightest mass eigenstate $\tilde{\chi}_1^0$ of the four neutralinos $\tilde{\chi}_i^0$, $i = 1, \ldots, 4$, which are mixtures of the four neutral gauge and Higgs fermions (gauginos, Higgsinos), $\tilde{\gamma}$, $\tilde{Z}$, $\tilde{H}_1^0$ and $\tilde{H}_2^0$. Due to its stability and weak interaction, the LSP is responsible for the "classical" experimental SUSY signature of missing energy. Besides the neutralinos, there are two pairs of charginos $\tilde{\chi}_i^{\pm}$, $i = 1, 2$, mixtures of the fermionic partners of the charged gauge and Higgs bosons.

The masses and couplings of the neutralinos/charginos depend on the familiar set of SUSY parameters M, M', μ and $\tan\beta = v_2/v_1$. M and M' are the $SU(2)$ and $U(1)$ gaugino masses, respectively, μ is the Higgsino mass parameter and $v_{1,2}$ are the vacuum expectation values of the two Higgs doublets.

A further important ingredient is the assumption that all twelve types of squarks (6 flavours×2) and analogously the sleptons are essentially mass degenerate.

The two processes with potentially largest cross sections at HERA are associated selectron and sneutrino production[39]

$$e^{\mp} + p \to \left\{ \begin{array}{l} \tilde{e}^{\mp}_{L,R} + \tilde{q}_{L,R} + X \\ \overset{(-)}{\tilde{\nu}} + \tilde{q}_L + X \end{array} \right\} \text{ via } \left\{ \begin{array}{ll} \text{neutralino} & (\tilde{\chi}^0) \\ \text{chargino} & (\tilde{\chi}^{\pm}) \end{array} \right\} \text{ exchange,} \tag{17}$$

where $\tilde{\nu}$, $\tilde{e}_{L,R}$ and $\tilde{q}_{L,R}$ are the sneutrino, the left and right selectron and squark, respectively.

The produced sfermions decay into ordinary fermions and neutralinos, possibly including cascade decays

$$\tilde{f} \to \left\{ \begin{array}{lll} f + \tilde{\chi}_1^0 ; & & \\ f + \tilde{\chi}_2^0 & \to f + (f'\bar{f}') + \tilde{\chi}_1^0 ; \\ f' + \tilde{\chi}_1^{\pm} & \to f' + (f\bar{f}'') + \tilde{\chi}_1^0 . \end{array} \right. \tag{18}$$

As an illustration,[39] the total cross sections for the two reactions (17) are displayed in Fig. 8 as functions of $m_{\tilde{e}_L} + m_{\tilde{q}_L}$ and the gaugino mass M, summed over all sqark flavours for $\sqrt{s} = 314$ GeV, $\tan\beta = 4$ and $\mu = -200$ GeV. Apparently, the $\tilde{e}$ production cross section (right) exceeds 0.1 pb only if $m_{\tilde{e}_L} + m_{\tilde{q}_L} < 190$ GeV (and

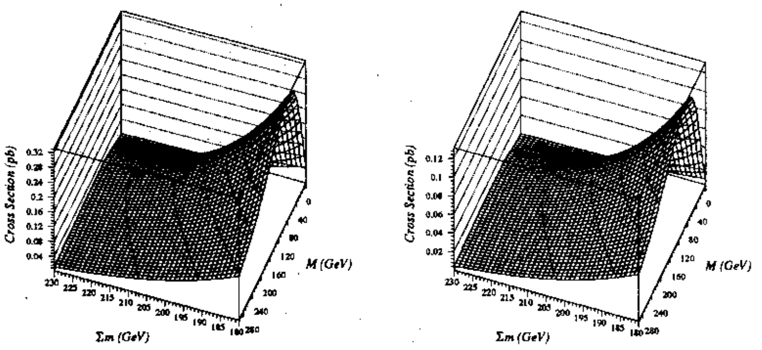


Fig. 8. Associated sneutrino (left) and selectron (right) production cross sections at HERA.[39]

$M \simeq 100$ GeV). In a wide range of the SUSY parameter space accessible at HERA, $Br(\tilde{e}_{L,R} \to e\tilde{\chi}^0_1) \simeq 100\%$. Although the $\tilde{\nu}$ production cross section (Fig. 8 left) is larger, the explorable mass range is similar. The reason is that the direct $\tilde{\nu}$ decay into $\tilde{\chi}^0_1$ is invisible, such that the branching ratio for visible decays (18) via a chargino and a charged lepton reduces the sensitivity to $m_{\tilde{\nu}} + m_{\tilde{q}}$.

The present and near future experimental situation with regard to slepton-/squark searches at HERA, LEP and the Tevatron is summarized in the "HERA discovery window for SUSY partners", Table 4. Some important comments need to be made, however.

The associated slepton production cross sections (17) at HERA mainly depend on the *sum* $m_{\tilde{l}} + m_{\tilde{q}}$ of slepton and squark masses and the gaugino mass M. LEP experiments[40] have provided the bounds $m_{\tilde{f}} > m_Z/2$. The slepton mass bounds from LEP may be combined with the squark bounds[41] from CDF (Fig. 9). If the possibility of cascade decays of squarks and gluinos is ignored (Fig. 9 left), the resulting limits are $m_{\tilde{l}} + m_{\tilde{q}} > 170$ GeV (independent of $m_{\tilde{g}}$) and the HERA discovery window would almost be closed[42] (c.f. Table 4). However, as Fig. 9 (right) illustrates, the resulting bounds for $m_{\tilde{q}}$ are strongly model dependent. For example, if $m_{\tilde{q}} > 400$ GeV and cascade decays are taken into account,[43] there is no limit anymore on $m_{\tilde{q}}$, and correspondingly, more room for discovery at HERA. Moreover, we note that the cross sections (17) are peaked around $m_{\tilde{g}} \simeq M/0.3 \simeq 300$ GeV (Fig. 8), where the squark mass bound from CDF (Fig. 9 left) is (presumably) still $O(150)$ GeV.

In summary: The HERA discovery potential for SUSY partners based on the MSSM appears limited. However, in view of the model dependence of the squark

Table 4. **HERA** discovery window for SUSY partners in comparison with searches at e^+e^- and hadron colliders. All masses are in GeV.

HERA Discovery Window for SUSY Partners					
	$m_{\tilde{l}}$	$m_{\tilde{q}}$	$m_{\tilde{g}}$	$m_{\tilde{l}} + m_{\tilde{q}}$	Remarks
LEP[40]	> 45	> 45		> 90	
⊕					
CDF[41,21] ('92)		> 126	> 152	> 170	no cascades
		c.f. Fig. 9	if < 400	?	
4.4 pb^{-1}		no limit	if > 400	> 90	with cascades[43]
HERA[42] 100 pb^{-1}				> 180 – 200	cascade decays?
CDF[21] (≥'93) ≃ 25 pb^{-1}	> 150	> 180		> 200	no cascade decays

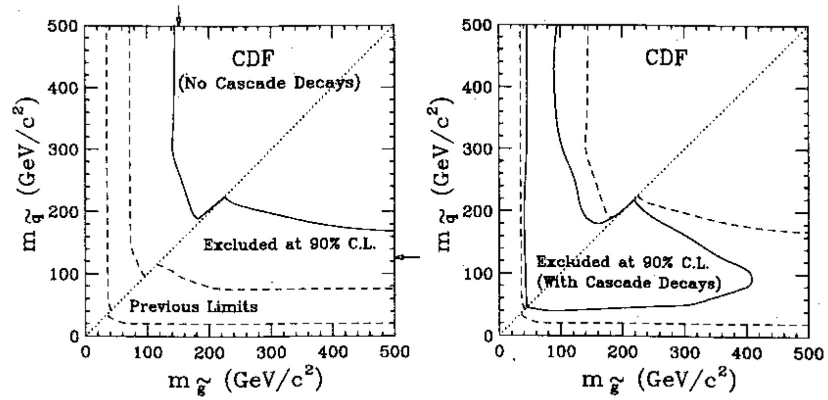


Fig. 9. CDF limits[41] on squark and gluino masses without (left) and with (right) cascade decays.[43]

mass bounds from CDF, a systematic search at HERA appears certainly worthwhile. If enough luminosity has been accumulated, it may also be rewarding to study $O(\alpha^3)$ processes, like[39]

$$e^{\mp} + p \rightarrow \tilde{e}^{\mp}_{L,R} + \tilde{\chi}^0_i + q + X, \qquad (19)$$

which for large squark masses above 150 GeV, say, involve mainly photon exchange in the t channel and depend only weakly on $m_{\tilde{q}}$.

4.2. Light Stop ($\tilde{t}$) Production

An interesting variant of the MSSM corresponds to the possibility of a relatively light stop[44] (scalar top) $\tilde{t}$, which may have escaped detection in all current experiments, as will be discussed.

The possibilities for discovering a light stop at HERA have been studied in detail in Refs. .[45,46]

In the MSSM based on N=1 supergravity GUT's, the SUSY partners $\tilde{f}_{L,R}$ of left and right handed matter fermions are generally mixed and their mass term has the structure[45,47]

$$-\mathcal{L}_{\text{mass}} = \left(\tilde{f}^*_L, \; \tilde{f}^*_R \right) \begin{pmatrix} m^2_{\tilde{f}_L} & a m_f \\ a^* m_f & m^2_{\tilde{f}_R} \end{pmatrix} \begin{pmatrix} \tilde{f}_L \\ \tilde{f}_R \end{pmatrix} ; \qquad a \sim O(m_{\tilde{q}_{L,R}}). \qquad (20)$$

Since the off-diagonal matrix elements are proportional to the masses of the ordinary fermions, the SUSY partners $\tilde{l}_{L,R}$ and $\tilde{q}_{L,R}$ of leptons and light quarks, respectively, are the mass eigenstates to good approximation. For the stop $\tilde{t}$, however, *strong mixing* may be natural in a large region of parameter space, due to the heavy mass of the top quark! One of the mass eigenstates $\tilde{t}_{1,2}$ obtained from diagonalization of (20)

$$\begin{array}{ll} \tilde{t}_1 = & \cos\theta_t \, \tilde{t}_L + \sin\theta_t \, \tilde{t}_R \\ \tilde{t}_2 = & -\sin\theta_t \, \tilde{t}_L + \cos\theta_t \, \tilde{t}_R \end{array} ; \qquad \tan 2\theta_t = \frac{2 a m_t}{m^2_{\tilde{t}_R} - m^2_{\tilde{t}_L}}, \qquad (21)$$

may then be exceptionally light, with a mass

$$m_{\tilde{t}_1} = \frac{1}{2}\left\{ m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R} - \sqrt{(m^2_{\tilde{t}_L} - m^2_{\tilde{t}_R})^2 + 4a^2 m^2_t} \right\}, \qquad (22)$$

even considerably lighter than the top mass and the other squark masses!

Note that in this case for $m_{\tilde{\chi}^0_1} > 10$ GeV, the CDF bounds (c.f. Fig. 9) do not apply anymore.[44] Firstly, the production cross section for a single squark type is smaller by a factor 12 than the one for mass degenerate squarks underlying Fig. 9. Secondly, for a relatively light $\tilde{t}_1$, a non-zero LSP mass ($m_{\tilde{\chi}^0_1} > 19$ GeV from LEP data[18]) deteriorates the missing transverse energy signature.[44] As to the bounds on $m_{\tilde{t}_1}$ from LEP, they depend on the mixing angle θ_t, Eq. (21), which may even be tuned such that $\tilde{t}_1$ decouples from the Z^0!

The dominant production mechanism at HERA is $\tilde{t}_1$ pair production via photon-gluon fusion[45,46] and the dominant decay has been convincingly estimated to be the flavour violating two-body decay[47]

$$\tilde{t}_1 \rightarrow c + \tilde{\chi}^0_1 ; \qquad \text{for } m_{\tilde{t}_1} < 60 \text{ GeV}, \qquad (23)$$

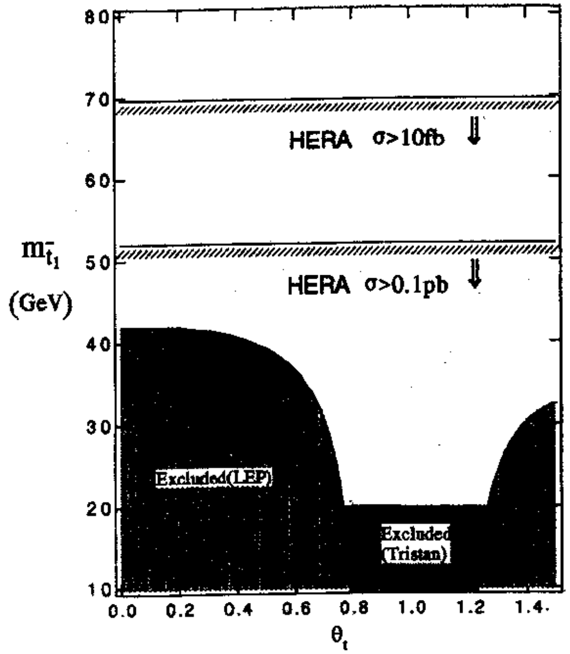


Fig. 10. HERA discovery window[45,46] for a light stop ($\tilde{t}_1$) and the regions in the ($m_{\tilde{t}_1}$, θ_t) plane excluded by LEP and Tristan.

such that the signal consists in two charm jets and missing transverse energy.

The HERA discovery window for a light stop is illustrated in Fig. 10 taken from Ref. .[45]

In summary: Looking for a light stop up to masses $O(50)$ GeV clearly represents an opportunity for HERA. The resulting mass bounds will be independent of the stop mixing angle θ_t.

4.3. Broken R Parity

Recently, there has been much theoretical,[48] cosmological[49] and phenomenological[46,50–52] work on the more general supersymmetric extension of the SM with explicitly broken R parity. In such a framework, the particle content is still kept minimal, but one now allows for *all* gauge invariant and supersymmetric terms in the superpotential including R parity violating terms. These break either lepton (L)- or baryon (B) number. Interaction terms giving rise to excessive proton decay or too much lepton number violation may be suppressed by means of discrete symmetries.

The implications of R parity violation for HERA have been studied in detail in Refs. .[52] In Refs. [46,51] the possibility of a light stop discussed previously is studied in an R parity violating framework. Let me briefly summarize some essential implications.

The phenomenology of R parity violation differs from that of the MSSM in two main aspects:

- The LSP is no longer stable, since it is not protected by a symmetry. It may thus decay within or outside the detector. The characteristic missing transverse energy signal is therefore absent or deteriorated.
- *Single* production (formation) of SUSY partners is now possible, since the final state is no longer restricted to be R parity even.

Broken R parity represents the least "orthodox" SUSY scenario discussed so far; yet, the signals at HERA would be analogously spectacular as those of leptoquarks, namely resonant $e^{\mp}q$ formation peaks of (single) squarks in the x distribution.

Among the possible gauge invariant and supersymmetric additional terms with R parity violation in the superpotential, the following L breaking Yukawa term is of particular interest at HERA[52]

$$W_{\mathrm{R\ breaking}} = \lambda'_{i\,j\,k} \cdot (L_i Q_j D^c_k)_F + \cdots . \tag{24}$$

L, Q and D^c are the (left handed) lepton doublet, quark doublet and antiquark singlet of chiral superfields, respectively, and summation over the generation indices i, j, k is implied. The couplings $\lambda'_{i\,j\,k}$ are dimensionless and the subscript F denotes the SUSY invariant part in the above product of chiral superfields.

For e$^-$ beams at HERA we identify i=1 and obtain from Eq. (24) the following two distinct formation channels for (single) squarks after decomposition of the superfields into their particle and sparticle content

$$\lambda'_{1\,1\,k} \; : \; e^- + u \to \tilde{d}, \tilde{s}, \tilde{b} \; ; \qquad \left.\begin{array}{l} \lambda'_{1\,j\,1} \; : \; e^-\bar{d} \\ \lambda'_{1\,j\,2} \; : \; e^-\bar{s} \end{array}\right\} \to \tilde{u}^c, \tilde{c}^c, \tilde{t}^c. \tag{25}$$

The formation on the left is most promising since it involves valence quarks. Apparently, a large number of the $\lambda'_{1\,j\,k}$ couplings may be probed at HERA.

Unlike leptoquarks, there are *two* distinct squark decay patterns (each involving R parity violation), which may be explored.

$$\begin{array}{ll} \text{“Leptoquark type”} & : \tilde{q} \to \; q + \overset{(-)}{l} \\ \Delta L(HERA) = 2 & : \tilde{q} \to \; q + \tilde{\chi}^0_1 \to q + (e^+\tilde{e}^-) \to q + e^+ + (\bar{u}d). \end{array} \tag{26}$$

The second decay chain involves R parity violation only in the last step and gives rise to a clean lepton number violating signature in terms of the single positron in the final state. The price to pay are suppression factors from branching fractions. A more complete discussion of the possible decay patterns may be found in Refs. .[52]

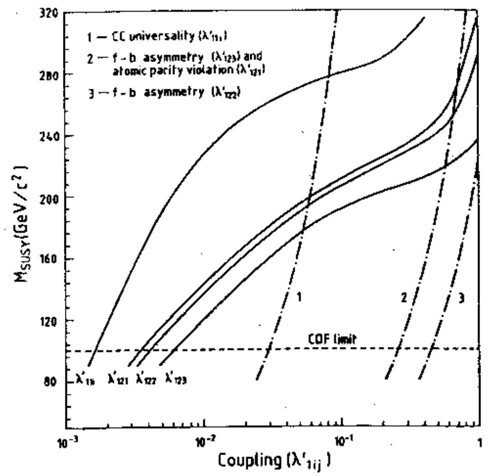


Fig. 11. HERA discovery window for squarks in case of R parity violation[52] for an integrated luminosity of 200 pb^{-1}. The regions to the right of the contours in the (m_{SUSY}, λ'_{1jk}) plane are excluded. Also shown are lower bounds on the ratio $m_{SUSY}/\lambda'_{1\,j\,k}$ from an evaluation of the virtual contributions of (single) squarks to various processes with R-even final states in the contact interaction limit.[53]

The HERA discovery window for squarks with R parity violation is illustrated in Fig. 11 assuming an integrated luminosity of 200 pb^{-1}.

There are a number of existing lower bounds on the ratio $m_{\tilde{q}}/\lambda'_{1\,j\,k}$ from an evaluation of the virtual contributions of (single) squarks to various processes with R-even final states in the contact interaction limit.[53] They are also displayed in Fig. 11.

In summary: At HERA, at large reach for squark masses and their couplings may be explored in case of R parity violation. One finds, for example, that squark masses as large as $m_{\tilde{q}} \simeq 270$ GeV and a small coupling $\lambda'_{1\,1\,k} \simeq 0.08$ should be observable. The discovery potential is comparable to that for leptoquarks.

5. Virtual Effects from New Heavy Bosons

5.1. The Contact Interaction Limit

The concept of contact interactions represents a general and convenient (effective Lagrangian) tool to study the *virtual* effects of new particles, too heavy to be produced at the energy under consideration. Sufficiently heavy particles X cease to propagate and thus new contact terms and modified vertices arise from "contracting" the heavy particle propagators to a point. Besides being *completely general**, the contact interaction limit of heavy particle exchanges also enjoys some economy. The separate dependences of amplitudes on couplings $g_{X\to i,f}$ to channels i, f and mass m_X reduce to the dependence on effective couplings with dimension [mass^{-2}]

$$\eta_{fi} \equiv \frac{g_{X\to f}\, g_{X\to i}}{m_X^2}. \tag{27}$$

The study of contact interactions has by now become a "classical" subject, canonically culminating in tables with bounds on *selected* contact interaction coefficients (with the rest assumed to vanish!).

Let me summarize here a new type of $(\bar{e}e)(\bar{q}q)$ contact interaction analysis for HERA, which –unlike previous studies– is model *independent.*[55] It allows *a posteriori* for a concise confrontation with any model involving new heavy bosons. This implies that *all* relevant contact term coefficients have to be treated simultaneously as free parameters, with correlations among them taken properly into account!

5.2. *A Model Independent Contact Interaction Analysis*

Any model corresponding to the exchange of some heavy bosons X in the $eq \to eq$ subprocess at HERA, may be "projected" in the limit of large boson mass m_X onto a certain complete set of four-fermion interaction terms. At HERA,in the NC sector, it may be argued that the eight vector-vector terms,

$$O^q_{ij} \equiv (\bar{e}_i\gamma_\mu e_i)(\bar{q}_j\gamma^\mu q_j); \qquad \begin{cases} i,\, j & = L,\, R \\ q & = u,\, d, \end{cases} \tag{28}$$

are sufficient in practice (The remaining scalar-scalar and tensor-tensor terms are negligible because of the helicity flip involved, producing factors $\propto m_e$).

The NC analysis was, therefore, based on a contact interaction Lagrangian involving the terms (28)

$$\mathcal{L}^{\rm NC}_{\rm contact} = \sum_{q=u\,d}\ \sum_{i,j=L,R} \eta^q_{ij} O^q_{ij}, \tag{29}$$

which allows for a description of the (dominant) virtual effects from any new heavy bosons at HERA in terms of $2\cdot 4 = 8$ parameters[55] η^q_{ij} with dimension [mass^{-2}], taking positive or negative values. In models with heavy bosons X with some generic coupling g_X and mass m_X, all η's are, of course, proportional to $(g_X/m_X)^2$. The analysis was carried out along two different lines[55]:

i) *Theoretically:* The coefficients η^q_{ij} were computed for all popular models of interest involving heavy bosons [Z' models: $Z'_{A\ldots C}$, Z'_{L-R}, $Z'_{SM-\rm coupl.}$, all 10 leptoquarks of Sect. 2]. In each case, one unknown/model, m_X/g_X, remains.

---

*While contact interactions have been popularized in the context of composite quarks and leptons,[54] they are by no means restricted to compositeness.

ii) *Experimentally:* A model independent statistical χ^2 analysis was performed with the contact terms (29) added to the SM Lagrangian and the eight parameters η^q_{ij} left free, simultaneously. For the time being, the "experimental data" were substituted by the SM expectations ($\eta^q_{ij} = 0$) for the observables considered. ($2\,\sigma$) exclusion domains for the parameters η^q_{ij} were derived *including full error correlations*, both for unpolarized and for longitudinally polarized $e^\mp$ beams. All subsequent results are based on a standard reference luminosity, $\int \mathcal{L}dt = 100$ pb^{-1}, standard x, y cuts in order to keep the importance of radiative corrections under control and an overall systematic error of ± 5 %.

5.3. *The HERA Discovery Window*

A much more detailed description of the performed contact interaction analysis may be found in Ref..[55] Let me merely illustrate here the type of results one may expect and some important applications.

The output of the model independent statistical analysis characterized in the previous subsection, comes in form of $8\cdot 7/2 = 28$ two-dimensional exclusion contours (corresponding to $\Delta\chi^2 = 4$) in the $\eta^q_{ij} - \eta^{q'}_{kl}$ parameter planes. There are 6 exclusion contours referring to up-quark coefficients only, 6 contours referring to down-quark coefficients, and 16 contours, where up-quarks are correlated with down-quarks. These contours are displayed for the case of unpolarized e^- beams in Fig. 12.

The inside regions are always allowed and the origin ($\eta^q_{ij} = 0$) corresponds to the SM (marked by a cross). It is evident from Fig. 12 that the method works and leads to strong, *model independent* constraints for the eight contact interaction coefficients η^q_{ij}.

The predictions for the η^q_{ij} from any particular model may now be superimposed, corresponding to specific *vectors* (of prescribed directions) through the origin (SM) in each η plot. From their intersection with the exclusion contours, best limits on m_X/g_X are then derived. This is illustrated nicely for the case of a variety of popular Z' models[55,56] in Fig. 13.

It is immediately obvious that the sensitivity to L-R symmetrical Z' models is close to optimal at HERA, while model C is about worst.

In the same way, 95 % confidence level (CL) bounds for $m_{LQ}/\lambda_{L,R}$ for all ten species of leptoquarks of Sect. 2 have been obtained.[55] Fig. 14 illustrates these results for the case of the "$SU(5)$-saving" leptoquark $\tilde{S}_{1/2}$ (c. f. Sect. 2) along with the corresponding expected direct search limits from a simulation.[4] The range of sensitivity to leptoquarks in parameter space is considerably enlarged by taking into account their virtual effects, too.

In summary: A model independent analysis of virtual effects from new heavy boson exchange at HERA for $m_X > \sqrt{s}$, may represent a powerful complement to direct new particle searches for $m_X < \sqrt{s}$. The presented analysis allows to judge at a glance of the eye, whether HERA will be particularly sensitive (or insensitive) to the heavy bosons of *any* given model; or, turned around, to find the "HERA tailored" model in a whole class of related ones.[56]

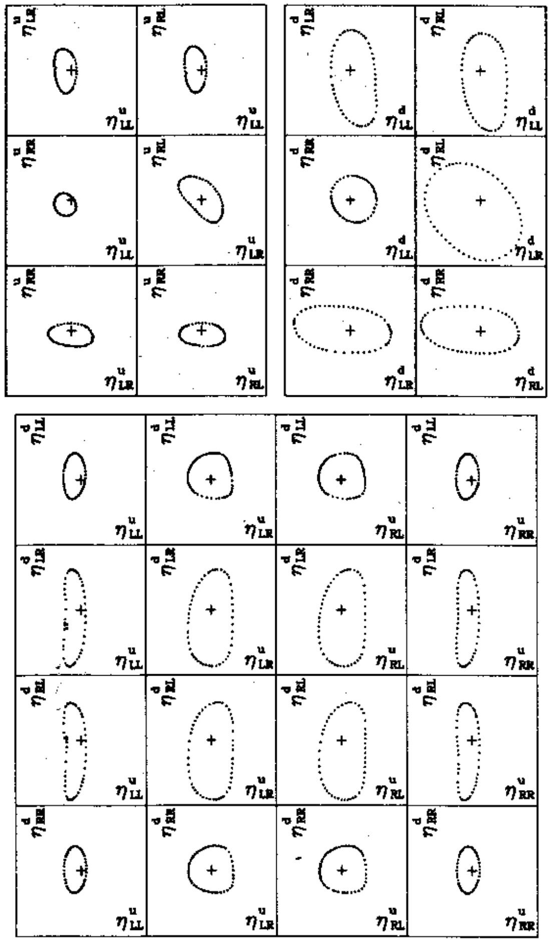


Fig. 12. Complete set of 28 'shadow projections' of the model independent allowed parameter domain in eight dimensional parameter space for unpolarized e^- beams.[55] All correlations among the eight contact interaction coefficients η^q_{ij} are included. Each side of the boxes ranges between $(-25, +25)\,\mathrm{TeV}^{-2}$ and the origin (cross) corresponds to the SM.

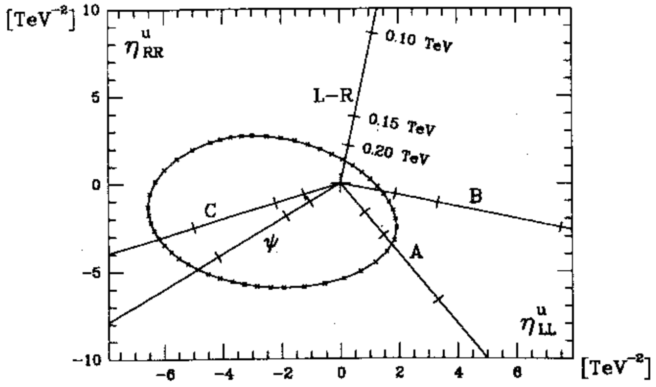


Fig. 13. Model independent exclusion contour from Fig. 12 (unpolarized e^- beam) with five Z' models superimposed.[55] While the L-R symmetrical model is close to optimal for HERA, model C is about worst. The various tickmarks refer to respective m_X/g_X bounds at 95% CL in TeV.

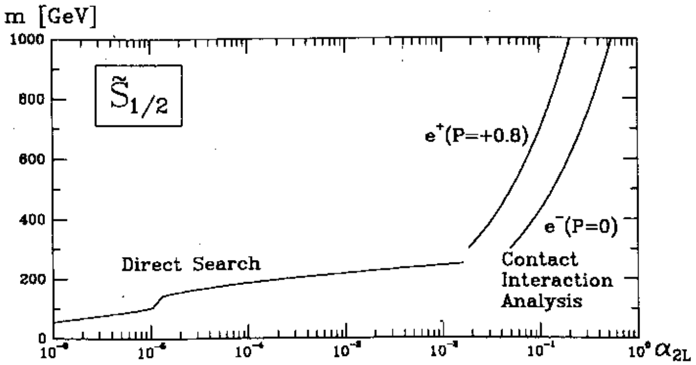


Fig. 14. Possible information from HERA on the interesting, so-called "$SU(5)$-saving" leptoquark $\tilde{S}_{1/2}$, both from direct searches[4] and the described model independent analysis of contact interactions.[55] The mass limit of $\tilde{S}_{1/2}$ (95% CL) versus the coupling $\alpha_{2L} = \tilde{h}^2_{2L}/4\pi$ is displayed.

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