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W. Buchmüller
Deutsches Elektronen-Synchrotron DESY, Hamburg

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NEW LEPTONS, QUARKS AND LEPTOQUARKS IN HIGH ENERGY e^+e^- ANNIHILATION [*]

W. Buchmüller
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

ABSTRACT

Extensions of the standard model predict new spin-$\frac{1}{2}$ and spin-0 particles which may be colour singlets or colour triplets. We study pair production and single production of these particles in e^+e^- annihilation at 500 GeV center-of-mass energy. With the projected NLC luminosity, in most cases the production of new particles with masses close to the kinematical limit will be possible. We also discuss properties of final states resulting from heavy neutrino decays.

1. Theoretical Framework

Within the standard model strong and electroweak interactions are described by the gauge group $G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$. However, despite the extraordinary phenomenological success of the standard model it is widely believed that G_{SM} is only the low energy remnant of a more fundamental, unified group and it is conceivable that new gauge interactions become visible already at TeV energies. Particular attention has been given to models with right-handed currents[1] based on the symmetry group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ and to models with an additional $U(1)_X$ symmetry[2]. Both extended gauge groups can be imbedded into the unified group E_6 via the following chains:

$$\begin{aligned}
(i)\; G_{SM} &\subset SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{Y'} \\
&\subset SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \\
&\subset SO(10) \subset E_6\,, \\
(ii)\; G_{SM} &\subset G_{SM} \times U(1)_X \\
&\subset E_6\,.
\end{aligned} \tag{1}$$

Here Y' denotes the remaining $U(1)$ charge in $SO(10)$ which is orthogonal to the standard model hypercharge, and X is one linear combination of the two additional $U(1)$ charges in E_6 which are usually denoted by ψ and χ (cf. Ref.2). The unified groups E_6 and $SO(10)$ have to be spontaneously broken at the unification mass scale $\Lambda_{GUT} > 10^{15}\,GeV$ in order to be consistent with experimental bounds on the proton lifetime. However, as suggested by many extensions of the standard model, the subgroups $SU(2)_R, U(1)_{Y'}, U(1)_{B-L}$ or $U(1)_X$ may remain unbroken down to a mass scale of order 1 TeV.

Extended gauge theories also predict new fermions in addition to the quarks and leptons of the standard model, since all gauged currents have to be anomaly free. For the unified group E_6 the 27-plet is the basic building block for matter particles. It contains the 15 standard model fermions ("f_{OLD}") and 12 novel fermions ("f_{NEW}"):

$$\begin{aligned}
f_{OLD} &= \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, e_R, \begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R \\
f_{NEW} &= \nu_R; \begin{pmatrix} N_L \\ E_L \end{pmatrix}, \begin{pmatrix} N_R \\ E_R \end{pmatrix}, D_L, D_R; n.
\end{aligned} \tag{2}$$

The 12 standard model fermions are denoted in the usual way; all weak isodoublets are left-handed and all weak isosinglets are right-handed. The new fermions contain two weak isodoublets with the same hypercharge as the ordinary lepton doublet, two colour triplets with the same hypercharge as d_R and two fermions without colour and electroweak charges. The main difference between old and new fermions concerns the allowed mass terms: the old fermions can aquire mass only after the spontaneous breaking of the elektroweak gauge symmetry whereas direct mass terms are allowed for the new fermions. If the extended gauge group is contained in the unified group $SO(10)$, the only required new fermion is the right-handed neutrino ν_R. On the other hand, all 12 novel fermions are needed if E_6 is the smallest unified group containing $G_{SM} \times U(1)_X$.

From the requirement that the running Yukawa couplings of new heavy fermions, which obtain their mass from the Higgs vacuum expectation value, remain finite between the weak interaction scale Λ_{FERMI} and and the unification scale Λ_{GUT}, one can derive upper bounds on the fermion masses. In the special case of N_H additional heavy standard model generations, Bagger, Dimopoulos and Masso[3] obtained for heavy leptons the bound

$$m_L < 235/\sqrt{N_H}\,GeV\,. \tag{3}$$

Hence, pair production of such leptons would be kinematically allowed at NLC.

Unlike the new fermions, new scalar particles are not required by the self-consistency of extended gauge theories. However, like the Higgs-doublet, which is needed for spontaneous symmetry breaking, additional scalars may nevertheless exist. If the fundamental theory is supersymmetric one expects the same quantum numbers for fermions and scalars, and we will generically denote by $\tilde{f}$ the scalar which carries the same quantum numbers as the fermion f. The mass spectrum of the scalar particles is a priori unknown. "Light" scalars with masses below 1 TeV would play the role of Higgs particles, diquarks, dileptons or leptoquarks in the effective low-energy theory.

The production of new fermions and scalars in e^+e^- annihilation can proceed through the processes shown in Fig.1. The s-channel processes with virtual photon, Z and Z' boson and the t-channel exchange of a W_R yield pairs of new particles (Fig.1a-1c). Mass mixing between old and new fermions also leads to off-diagonal couplings of the massive gauge bosons Z and W_L. The corresponding mixing parameter ξ has to be smaller than about 0.1[4].

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In most cases this mixing is also responsible for the decay of the new, heavy fermions (cf. Fig.1e). The corresponding width is given by

$$\Gamma = C \cdot 30\,MeV \left(\frac{\xi}{0.1}\right)^2 \left(\frac{m}{200\,GeV}\right)^3 , \; C = O(1), \tag{4}$$

where m is the mass of the new fermion. In models with right-handed currents the three-body decay via virtual W_R exchange is also important for the decays of the new fermions.

We have chosen extended gauge theories with underlying E_6 symmetry as theoretical framework to discuss novel particles. This comprises new spin-0, spin-$\frac{1}{2}$ and spin-1 particles with various colour and electroweak quantum numbers. More exotic new particles are predicted by other extensions of the standard model, in particular by composite models.

2. Pair Production

Let us now consider the pair production cross sections for new fermions and scalars. It is convenient to normalize production cross sections in e^+e^- annihilation to the cross section for the electromagnetic production of μ-pairs

$$\sigma_0 = \frac{4\pi\alpha_{EM}^2}{3s} = \frac{347\,fb}{(s\,[500\,GeV])^2}. \tag{5}$$

For the NLC with 500 GeV center-of-mass energy an integrated luminosity of 20 fb^{-1} per year is projected. Hence, requiring 10 events per year, one would be sensitive to cross sections down to 0.5 fb.

The production of new particles, predicted by extended gauge theories, in e^+e^- annihilation has been studied by different authors. A detailed discussion can be found in the paper by del Aguila, Laermann and Zerwas[5] and in the report of Hewett and Rizzo[6]. Of particular interest for e^+e^- colliders are heavy leptons and also scalar quarks which may be difficult to disentangle from background at hadron colliders. Leptoquarks can be produced more efficiently in ep and pp high energy colliders. However, e^+e^- colliders could play an important role in determining their scattering. However, e^+e^- colliders could play an important role in determining their spins and their electroweak quantum numbers. This will be discussed in Section 4.

In Figs.2-5 production cross sections for heavy electrons (E), heavy Dirac neutrinos ($\nu_E \equiv N$), heavy Majorana neutrinos ($N \equiv n$) and scalar quarks ($D_0 \equiv \tilde{D}$) are shown, as computed by Djouadi et al.[7]. In brackets the relation is given between the notations of Eq.2 and the figures. The orders of magnitude of the corresponding cross sections are

$$\begin{aligned} \sigma(e^+e^- \to E^+E^-)/\sigma_0 &= O(1)\,, \\ \sigma(e^+e^- \to N\bar{N})/\sigma_0 &= O(0.5)\,, \\ \sigma(e^+e^- \to n\,n)/\sigma_0 &= O(0.05)\,, \\ \sigma(e^+e^- \to \tilde{D}\tilde{D}^*)/\sigma_0 &= O(0.1)\,. \end{aligned} \tag{6}$$

The production cross sections for Dirac leptons and scalar quarks are dominated by the standard model s-channel processes with virtual photon and Z-boson. The Majorana neutrino n can only be produced via the new Z' boson; hence the cross section is strongly dependent on $m_{Z'}$ which has been chosen to be 700 GeV. The cross sections for Majorana neutrinos and scalar quarks are suppressed for large masses close to the kinematic boundary due to the characteristic β^3 behaviour.

Fig.6 shows the production cross section for heavy mirror electrons[8], which have right-handed instead of left-handed weak interactions. As expected, the cross section is almost identical to the one for heavy electrons with left-handed weak interactions which is plotted in Fig.2. The small differences reflect the different couplings to the Z boson. Since the cross sections are rather large, it should be possible to discover all new particles with masses almost up to the kinematical limit of 250 GeV. A more detailed analysis of discovery limits has recently been performed by Djouadi et al.[7] For heavy leptons with $m_L = 250\,GeV$ and $\sqrt{s} = 1\,TeV$ a Monte Carlo study of signal and background has been carried out by Ahn et al.[9] who find that already a data sample of 1 fb^{-1} would yield a clean signal.

Finally, Fig.7 shows the production cross sections for heavy Dirac neutrinos in models with right-handed currents[10] for different values of the W_R mass. The production cross section for Majorana neutrinos is only slightly smaller, except for the strong β^3 suppression close to the phase space limit. Depending on the Higgs sector, in models with right-handed currents the mass of the neutral vector boson Z' is rather precisely determined in terms of the W_R mass, and the production cross sections are almost insensitive to the remaining uncertainty in $m_{Z'}$. It is remarkable that at the NLC the sensitivity to W_R masses extends to 2 TeV. The heavy Dirac (Majorana) neutrinos can be produced with masses up to 220 (200) GeV.

3. Heavy Neutrinos

It is instructive to consider the case of heavy Majorana neutrinos in more detail. The simplest extended gauge model, in which such Majorana neutrinos occur, contains one additional $U(1)$-symmetry, $U(1)_{Y'}$ (cf. Eq.1). The new charge Y' is chosen such that $B - L$, the difference of baryon and lepton number, is a local symmetry, and in addition to the standard model fermions the theory contains one right-handed neutrino ν_R for each generation. The gauge group is then spontaneously broken in two steps:

$$G_{SM} \times U(1)_{Y'} \xrightarrow{v'} G_{SM} \xrightarrow{v} SU(3) \times U(1)_{EM}. \tag{7}$$

The vacuum expectation value v' breakes $B - L$ and generates a Majorana mass matrix for the right-handed neutrinos,

$$m = hv'; \tag{8}$$

in the second step, the vacuum expectation value v breaks $SU(2)_L \times U(1)_Y$ to the symmetry $U(1)_{EM}$ of electromagnetic interactions and generates a Dirac mass matrix which connects left- and right-handed neutrinos,

$$m_D = g_\nu v\,, \tag{9}$$

where the Yukawa couplings h and g_ν are 3×3 complex matrices.

So far very little is known about the mass scale v' of $B - L$ breaking. It may be equal to Λ_{GUT}, the unification mass, but it could also be of order 1 TeV, as suggested by most superstring models. In the second case one expects heavy neutrinos with masses between a few tens of GeV and a few hundred GeV, which could be produced in e^+e^- annihilation at 500 GeV.

Assuming that the Majorana masses given by Eq.7 are larger than the Dirac masses of Eq.8 one can easily diagonalize the entire neutrino mass-matrix. One finds three heavy Majorana neutrinos N, with $N = N^c$, and masses

$$m_N = m + O(\frac{1}{m}), \tag{10}$$

and three light Majorana neutrinos, with $\nu = \nu^c$, which are identified with ν_e, ν_μ and ν_τ. Their masses are given by the "see-saw" formula[11]

$$m_\nu = -m_D \frac{1}{m} m_D{}^T + O(\frac{1}{m^3}). \tag{11}$$

If the Yukawa couplings h do not exceed the top-quark Yukawa coupling $g_t \approx 1$, the heavy neutrino masses satisfy an upper bound which can be expressed in terms of the new Z' vector boson mass[12]

$$m_{N_i} \leq 970\,GeV\,\left(\frac{m_{Z'}}{1\,TeV}\right) \tag{12}$$

Similar relations can also be derived for other new fermions in extended gauge models with $U(1)_X$-symmetry contained in E_6.

The mass-mixing between left- and right-handed neutrinos leads to couplings of the heavy neutrinos N_i to charged leptons and the light neutrinos ν_e, ν_μ and ν_τ in charged and neutral currents, respectively. The off-diagonal neutral current couplings are given by the matrix $\xi_{ij} = (m_D/m)_{ij}$, $i, j = 1, 2, 3$ (cf. Fig.8). The charged current couplings are $(V\xi)_{ij}$ where V is the analogue of the Kobayashi-Maskawa matrix in the lepton sector. Charged and neutral currents are of $V - A$ type.

The mixing angles ξ_{ij} are constrained by precision measurements of various electroweak observables. From charged current universality one obtains[13]

$$\lambda_e \equiv \sum_{i=1}^{3} |\,\xi_{ej}\,|^2 < 1 \cdot 10^{-2}\,. \tag{13}$$

It may be possible to improve this bound to $3 \cdot 10^{-3}$ from projected measurements of forward-backward and polarization asymmetries in decays of the Z-boson.

The single production of heavy neutrinos[14] is dominated by the t-channel exchange of a W_L boson. For neutrinos masses below 200 GeV one finds the rather large cross section

$$\sigma(e^+e^- \to \nu N) \approx 1pb\,\left(\frac{\xi}{0.1}\right)^2\,. \tag{14}$$

For an integrated luminosity of 20 fb^{-1} this corresponds to 20.000 events! Fig.9 shows the total neutrino cross section for neutrino masses of 150, 300 and 1000 GeV as function of the center-of-mass energy. The cross section is dominated by t-channel W_L-exchange. Fig.10 shows the corresponding cross sections for the s-channel Z-boson contribution which are less than 1% of the total cross section. The t-channel W_L-exchange also dominates the single production cross section of heavy electrons (E) [7].

Heavy neutrinos decay mostly into charged leptons and W_L-bosons, which yield, most of the time, two jets (cf. Fig.11). Fig.12 shows the transvers momentum distribution of the final state charged leptons for two values of m_N. Clearly the average transvers momentum $< l_T >$ is very sensitive to the mass difference $m_N - m_W$. For $m_N = 200\,GeV$ one finds $< l_T > \approx 60\,GeV$.

A rough estimate of the discovery limits at the NLC can be obtained by requiring 20 events with an integrated luminosity of 20 fb^{-1}. Due to the large total cross section one finds that for a mixing angle $\xi_{eN}^2 = 10^{-2}$ heavy neutrinos can be produced up to the kinematic limit of 500 GeV, and that for a neutrino mass $m_N = 300\,GeV$ one is still sensitive to a mixing angle $\xi_{eN}^2 = 10^{-5}$. A more detailed Monte Carlo study[15] yields a sensitivity for ξ_{eN} of about 10^{-4}.

It is conceivable that mixing angles are much larger for the second and third families than for the first one, i.e., $\xi_{eN} \ll \xi_{\mu N}, \xi_{\tau N}$. In this case the t-channel W_L-exchange would be irrelevant and only the Z-boson would contribute in the s-channel. For $\xi_{\mu,\tau N} = 10^{-2}$ one is sensitive to neutrino masses up to 300 GeV.

In order to distinguish Dirac from Majorana neutrinos one has to study angular distributions. This is different from electron-proton scattering where it suffices to measure the charge of the final state lepton. For $\sqrt{s} = 200\,GeV$ and $m_N = 150\,GeV$ both angular distributions are shown in Fig.13. At $\sqrt{s} = 500\,GeV$ the production becomes much more peaked in forward and backward directions.

In comparision with ep scattering the main advantage of e^+e^- annihilation is the sensitivity to mixing angles involving the second and third generation, i.e., $\xi_{\mu N}$ and $\xi_{\tau N}$. For $\xi_{eN}^2 \approx 10^{-2}$, and also for right-handed currents, larger neutrino masses can be reached at LEP⊗LHC than at NLC.

4. LEPTOQUARKS

Leptoquarks are colour-triplet bosons with couplings to quark-lepton pairs. For leptoquarks with spin 0 and spin 1 these couplings can be dimensionless. The fermion number F, defined as $F = 3B + L$ where B and L are baryon and lepton number, respectively, can be either 0 or -2. The leptoquarks S and V (cf. Fig.14a) have $F = -2$, whereas R and U (cf. Fig.14b) have $F = 0$.

Leptoquarks are a generic prediction of unified theories[16]. Their masses, however, are model-dependent. The decays of very heavy leptoquarks ($m_{LQ} > 10^{10}\,GeV$) may be responsible for the generation of the baryon asymmetry of the universe. Yet many extensions of the standard model, in particular low energy superstring theories[3,4], also predict leptoquarks with masses of a few hundred GeV. Such leptoquark masses can be compatible with constraints from low-energy processes[17] if their couplings conserve baryon and lepton number.

Leptoquark exchange causes deviations from various standard model predictions, such as quark-lepton universality in charged current processes. Recently, Murayama and Yanagida[18] have pointed out that the addition of two isodoublet leptoquarks with hypercharge $\frac{1}{6}$, denoted as $\tilde{R}_2$, also has an intriguing effect on the running gauge couplings of the standard model. The most general Yukawa couplings of $\tilde{R}_2$ are

$$L_{YUK} = h\,\bar{d}_R l_L\,\tilde{R}_2 + c.c. \tag{15}$$

Hence, baryon and lepton number are automatically conserved and one easily verifies that also rare processes don't impose stringent constraints on the Yukawa couplings h. Fig.15 shows that the $SU(3)_C$, $SU(2)_L$ and $U(1)_Y$ gauge couplings meet each other at a unification scale close to $10^{15}\,GeV$, as naively expected in a unified theory. This is well known not to be the case in the standard model without additional particles (cf.Fig.16). Recently, it has been emphasized that the wanted unification is also achieved in supersymmetric extensions of the standard model[19] with a unification scale of about $10^{16}\,GeV$. Leptoquarks provide an interesting example of the known fact that unification of gauge interactions can also be achieved with "split" $SU(5)$ multiplets[20].

It is a straightforward exercise[21] to list all possible scalar and vector leptoquarks. In the case of fermion number $F = -2$ one finds for their $SU(3)_C \times SU(2)_L \times U(1)_Y$ quantum numbers and the quark-lepton pairs to which they couple,

$$\begin{aligned} S_1 &= (3^*,1)_{1/3} && e^-u,\ \nu d, \\ \tilde{S}_1 &= (3^*,1)_{4/3} && e^-d, \\ S_3 &= (3^*,3)_{1/3} && e^-u,\ e^-d,\ \nu u,\ \nu d, \end{aligned} \tag{16a}$$

and for fermion number $F = 0$ one obtains

$$\begin{aligned} R_2 &= (3,2)_{7/6} && e^-\bar{d},\ \nu\bar{u},\ e^-\bar{u}, \\ \tilde{R}_2 &= (3,2)_{1/6} && e^-\bar{d},\ \nu\bar{d}. \end{aligned} \tag{16b}$$

In general, single production and pair production of leptoquarks is possible in ep, e^+e^- and pp scattering via gauge and Yukawa couplings. A comparative discussion can be found in the review of Ellis and Pauss[22]. Leptoquarks with masses up to 1 TeV can be produced at the projected hadron colliders SSC and LHC. In ep scattering the ed- and eu-quark Yukawa couplings h are crucial for the production cross sections. A convenient measure for their strength is

$$k = \left(\frac{h^2}{4\pi}\right)/\alpha_{EM}. \tag{17}$$

For $k = 1$, HERA and LEP⊗LHC can test for leptoquarks up to the kinematic limit, and for $k \approx 10^{-2}$ one is still sensitive to leptoquark masses of 250 GeV [23] and 900 GeV [22], respectively.

Recently, Blümlein und Rückl[24] have systematically studied the pair production of all leptoquarks listed in Eq.15 in e^+e^- annihilation (cf. Fig.17). In this paper also references to previous work can be found. The cross sections for scalar leptoquarks are of the form

$$R_S \equiv \frac{\sigma_{LQ}}{\sigma_0} = \frac{3\beta^3}{8}\left(|\kappa(s)|^2 + O(h^2)\right), \tag{18}$$

where $\beta = \sqrt{1 - 4m_{LQ}/s}$ and κ denotes the gauge boson contribution. For $s \gg m_Z$ κ approaches a constant. The term proportional to the Yukawa couplings, h^2, is negligable if $h < 0.1$. The corresponding ratio R_V for vector leptoquarks has a dependence[24] on β and s different from R_S. The cross sections for scalar and vector leptoquarks vary over more than two orders of magnitude. For $m_{LQ} = 200\,GeV$ and two values of the Yukawa coupling $h \equiv \lambda_e$ they are listed in table 1. The corresponding quantities $|\kappa(s)|^2$ are shown in Fig.18. As the analysis of Blümlein and and Rückl shows, all cross sections are sufficiently large such that for all types of leptoquarks pair production is possible up to masses close to the kinematic limit of 250 GeV. Leptoquarks in this mass range would be discovered at hadron colliders. At the NLC the determination of their spins and their electroweak quantum numbers would then be possible by measuring total cross sections and angular distributions[24].

An interesting possibility is also the single production of leptoquarks in e^+e^- annihilation via the processes shown in Fig.19. For the leptoquark R_2 Hewett and Pakvasa[25] have evaluated single and pair production cross sections. From the corresponding discovery regions plotted in Fig.20 one reads off that leptoquark masses up to 450 GeV can be reached for $k = 1$. This exceeds the phase space limit of HERA, but lies significantly below the discovery limit of LEP⊗LHC. For $k > 10^{-2}$ the leptoquark masses accessible in single production are larger than the kinematical limit of pair production. Single leptoquark production can also be used to determine their electroweak quantum numbers.

One may wonder whether all the leptoquarks listed in Eq.15 really occur in any realistic theory. Frampton[26] has discussed a unified theory based on the gauge group SU(15), which corresponds to the symmetry of the kinetic term of one quark-lepton generation, where all scalar leptoquarks of Eq.15a are present in the effective low energy theory. This is a consequence of the pattern of spontaneous symmetry breaking. In addition the model predicts vector dileptons with quantum numbers $L = 2$ and $B = 0$.

The dileptons can be produced in pairs in e^+e^- annihilation, whereas single production is possible in e^-e^- collisions (cf. Fig.21). The e^-e^- mode of a linear collider would also be very interesting for the investigation of lepton number violation in the decay of heavy Majorana neutrinos[14].

5. Conclusions

What is the discovery potential of a 500 GeV linear collider with respect to new particles and what are its particular virtues compared to projected proton-proton machines with much higher center-of-mass energies?

We have adressed this question within the framework of extended gauge theories with underlying E_6 symmetry, which comprise colour triplet and colour singlet spin-0 and spin-$\frac{1}{2}$ particles, i.e., new leptons, quarks and leptoquarks. Clearly, the NLC would be ideally suited to discover new heavy leptons, which have no strong interactions and therefore comparatively small production cross sections in pp collisions. Pair production will be possible for leptons with masses close to the phase space limit,i.e.,

$$m_L < 250\,GeV\,. \tag{19}$$

In the case of mass mixing between light and heavy leptons also single production is possible. For mixings with the electron, $\xi_e^2 = 10^{-2}$, heavy neutrinos and also charged leptons can be produced up to the kinematical limit,

$$m_L < 500\,GeV\,. \tag{20}$$

In this case the cross section is dominated by t-channel $W-$ and $Z-$boson exchange. Due to the rather large cross section, for $m_L < 300\,GeV$ one is sensitive to mixings as small as $\xi_e^2 = 10^{-4}$. If only mixings to leptons of the second and third family are non-negligable, the cross section is given by the s-channel contribution of the $Z-$boson. For $\xi_\mu^2 = 10^{-2}$ or $\xi_\tau^2 = 10^{-2}$ one can then produce heavy neutrinos with masses

$$m_N < 300\,GeV\,. \tag{21}$$

Since the mass mixing is expected to be flavour-dependent, this case is of particular interest.

Pair production of scalar quarks and leptoquarks is possible for masses

$$m_{\tilde{D}}, m_{LQ} < 220 - 250\,GeV\,, \tag{22}$$

depending on the electroweak quantum numbers of the leptoquark. For sufficiently large Yukawa couplings, i.e., $k = 0.1$, single production of leptoquarks with masses up to 400 GeV is possible, which exeeds the phase space limit of HERA.

All particles discussed so far will also be produced in high energy pp colliders. However, due to comparetively small cross sections and large backgrounds their detection will be difficult. An exception are leptoquarks which have a large production cross section in hadron collisions and also a clean signature. Their production in e^+e^- collisions will be important for the determination of spin and electroweak quantum numbers.

Of particular interest is also the pair production of heavy neutrinos through right-handed currents. For neutrino masses below 170 GeV one is sensitive to a W_R mass of 2 TeV.

In summary, the NLC is well suited for the discovery of new particles and interactions in the lepton sector, which is complementary to projected hadron colliders. The center-of-mass energy of 500 GeV is sufficient to cover an important mass range where new particles can be expected if the standard model is the low energy remnant of a unified theory.

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7. Tables

Table 1. Total cross sections for pair production of leptoquarks with $m_{LQ} = 200\,GeV$ and two different Yukawa couplings $\lambda_{L,R} = h$. From Ref.24

leptoquark	type	$\sigma[fb]$	
		$\lambda_{L,R}/e = 0$	$\lambda_L/e = 0.3$
S_1	scalar	7	5
$\bar{S}_1$	"	106	99
$\vec{S}_3$	"	298	256
R_2	"	231	215
$\bar{R}_2$	"	73	63
V_2	vector	1403	1562
$\tilde{V}_2$	"	666	670
U_1	"	243	378
$\bar{U}_1$	"	1531	1531
$\vec{U}_3$	"	3287	3743

8. Figures

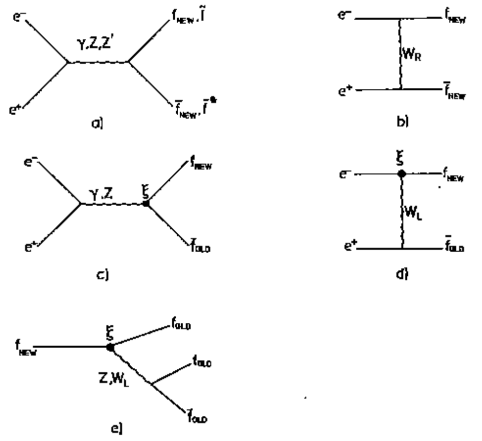


Fig.1 Single production and pair production of new fermions and scalars (a-d), and decay of new fermions (e); ξ is the mixing parameter.

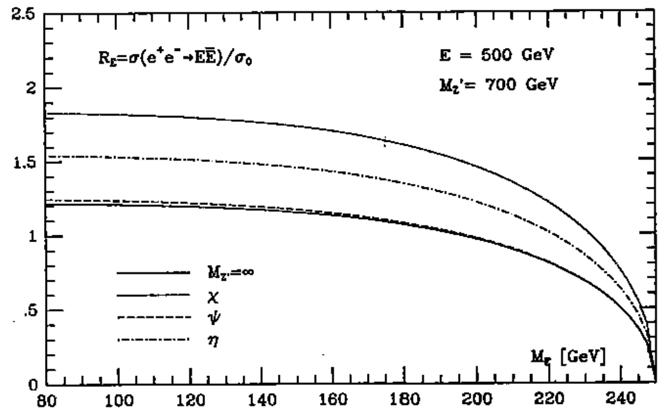


Fig.2 Pair production of heavy electrons via neutral vector bosons. From Ref.7.

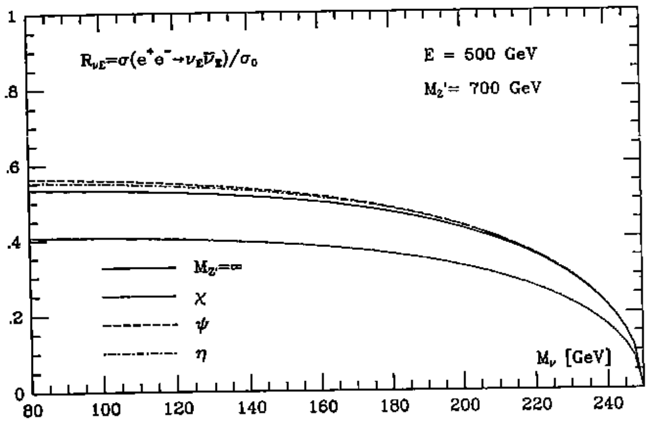


Fig.3 Pair production of heavy neutrinos via neutral vector bosons. From Ref.7.

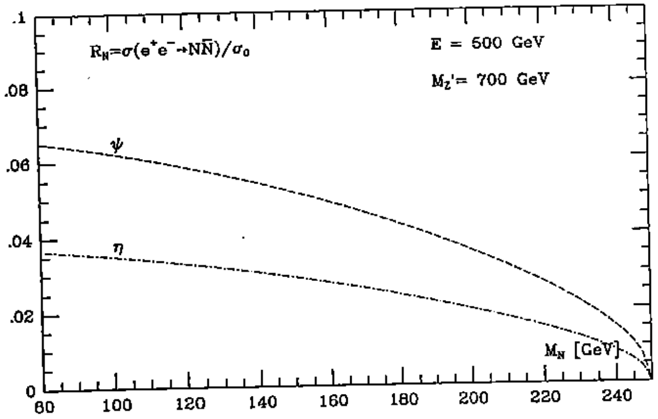


Fig.4 Pair production of weak isosinglet neutralinos via Z'-bosons. From Ref.7.

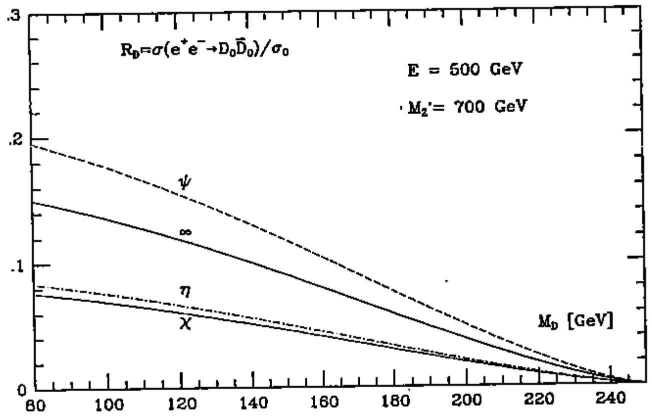


Fig.5 Pair production of scalar quarks via neutral vector bosons. From Ref.7.

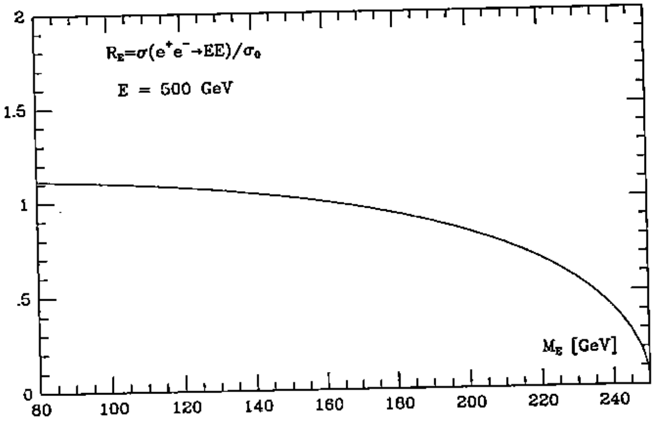


Fig.6 Pair production of heavy mirror electrons via the standard model Z-boson. From Ref.8.

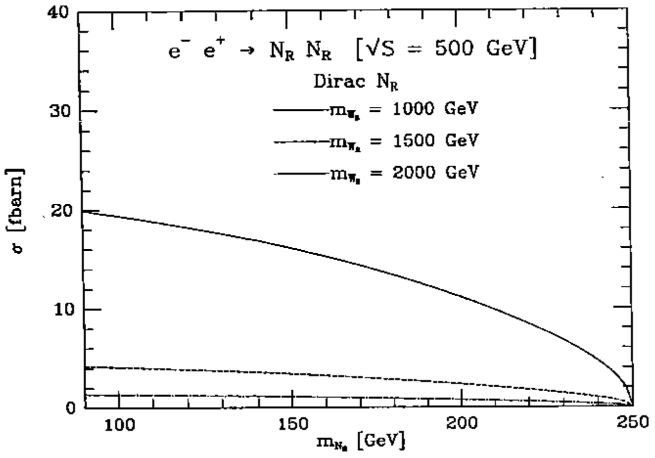


Fig.7 Pair production of heavy Dirac neutrinos via right- handed currents for three masses of the right-handed W-boson. From Ref.10.

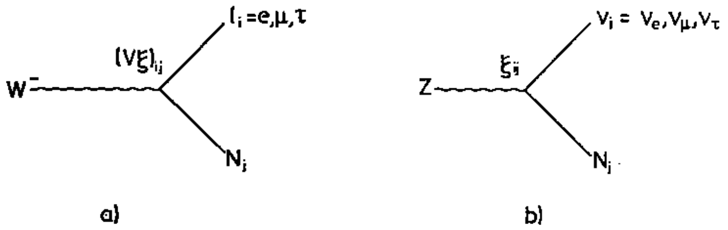


Fig.8 Charged and neutral current couplings between heavy neutrinos and ordinary leptons.

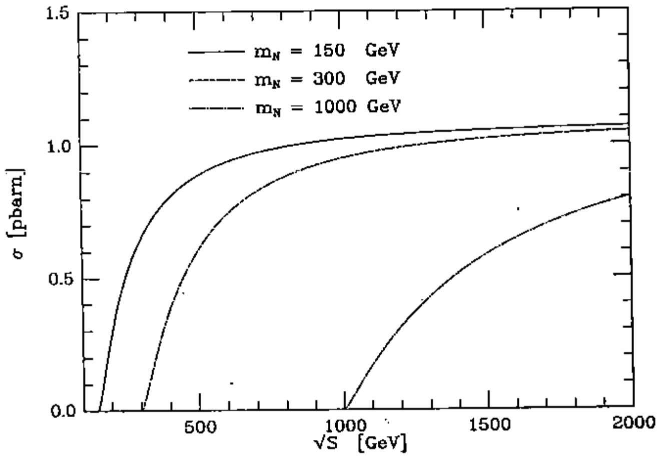


Fig.9 Total production cross section for single Majorana neutrino with $\xi^2 = 0.01$ for three different neutrino masses as function of $\sqrt{s}$. From Ref.14.

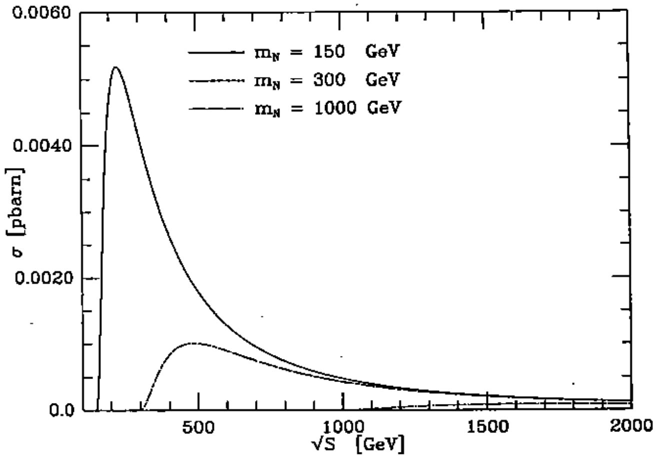


Fig.10 Z-boson contribution to the single neutrino production. From Ref.14.

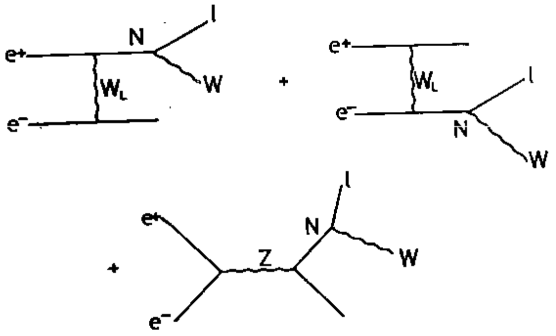


Fig.11 Production and decay of heavy Majorana neutrinos.

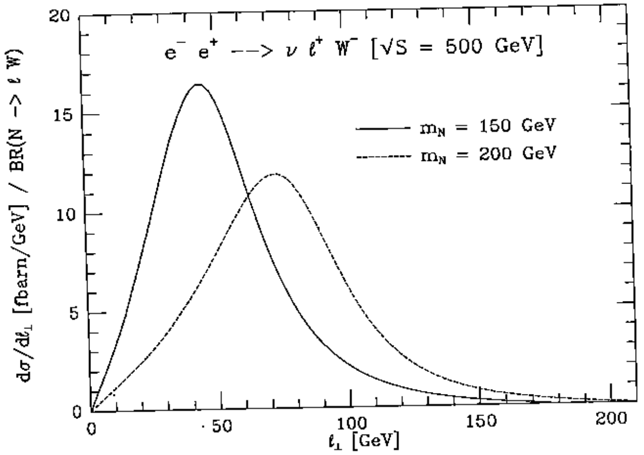


Fig.12 Transvers momentum spectrum of final state leptons for two different neutrino masses. From Ref.14.

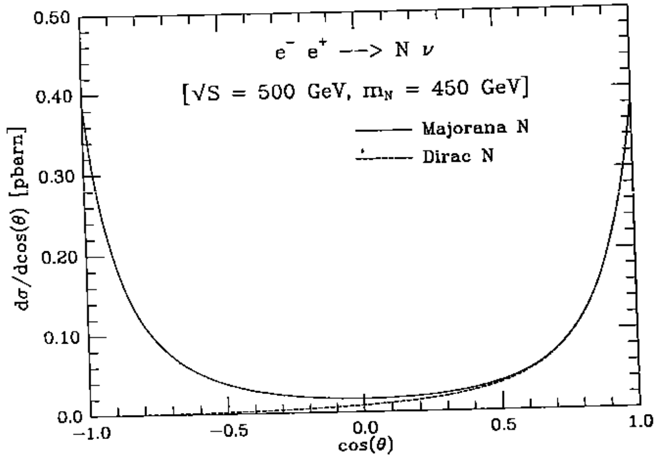


Fig.13 Angular distributions of Dirac and Majorana neutrinos. From Ref.15

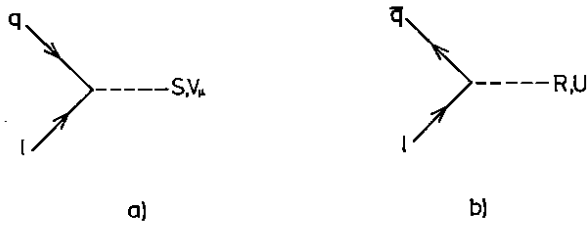


Fig.14 Leptoquarks with fermion number -2 (a) and 0 (b)

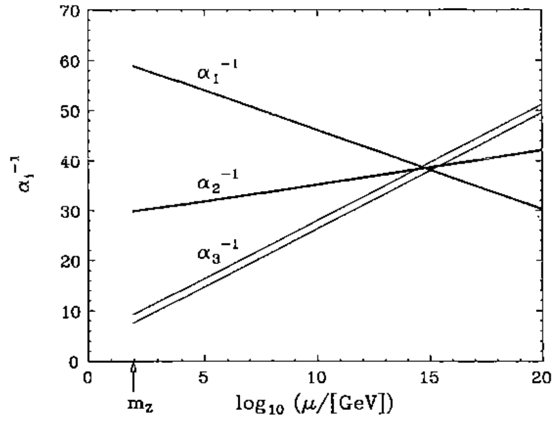


Fig.15 Scale dependence of gauge couplings in the standard model with leptoquarks. From Ref.18.

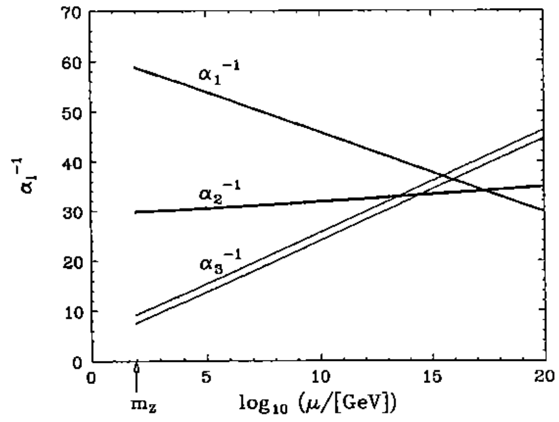


Fig.16 Scale dependence of gauge couplings in the standard model. From Ref.18.

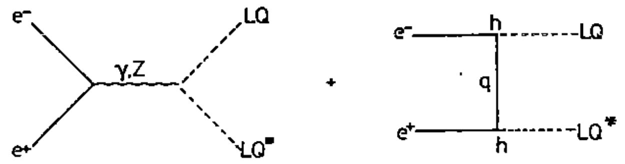


Fig.17 Pair production of leptoquarks through gauge and Yukawa interactions.

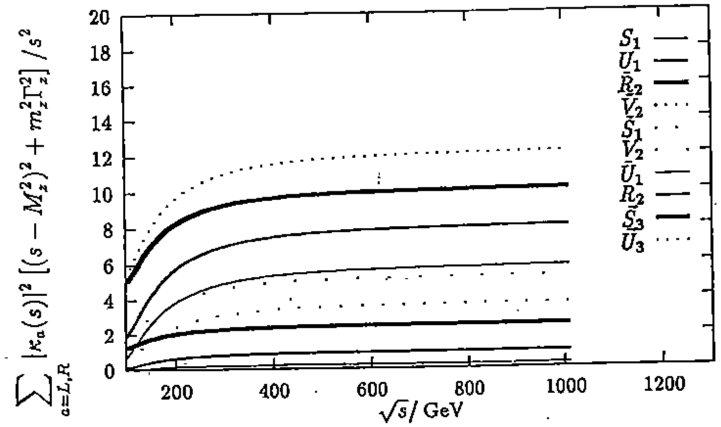


Fig.18 Rescaled production cross sections for all scalar and vector leptoquarks. From Ref.24.

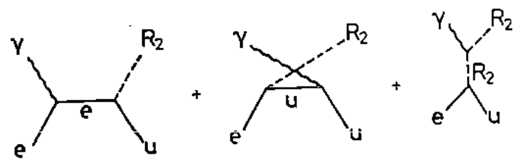


Fig.19 Contributions to single leptoquark production.

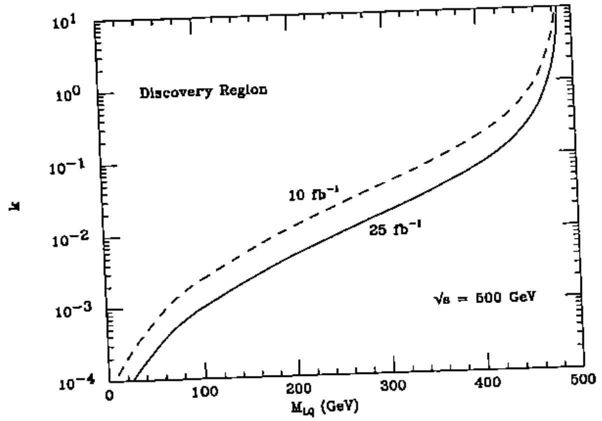
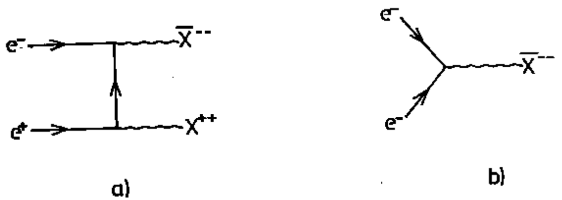


Fig.20 Discovery limits for leptoquarks as function of the Yukawa coupling strength; see text. From Ref.25.



a)

b)

Fig.21 Pair production and single production of dileptons.