LIMITS ON MIRROR LEPTONS IN ep COLLISIONS

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The production cross sections and decay characteristics of mirror leptons are calculated in high energy electron–proton collisions in a model with three mirror pairs of fermion families. For mirror mixing angles of the order of the present upper limits mirror lepton production at HERA ($\sqrt{s}=314$ GeV) is observable up to masses near 200 GeV. For a possible HERA upgrade ($\sqrt{s}=566$ GeV) this limit goes up to about 350 GeV and an ep collider in the LEP tunnel ($\sqrt{s}=1.4$ TeV) could cover the whole theoretically plausible range below 500 GeV.

A possible way of left–right symmetry restoration at high energies is the doubling of the light fermion spectrum by mirror partners at the scale of the electroweak symmetry breaking. Mirror pairs (with opposite chiral transformation properties) can easily be accommodated in many extensions of the minimal standard electroweak model (see, for instance, refs. [1–5] and the review [6]). Moreover, the non-perturbative lattice formulation of chiral gauge theories has difficulties to avoid the mirror doubling of the physical fermion spectrum. The root of these difficulties lies in the fermion doubling phenomenon in lattice regularization [7], implying the presence of mirror partners at the cut-off level. The decoupling of the mirror fermions by a high mass in the continuum limit is impossible if there is a cut-off dependent upper limit on their renormalized Yukawa couplings (for a discussion see ref. [8]). The mirror partners can also appear dynamically at strong bare Yukawa couplings, as it was shown in a prototype model using the hopping parameter expansion [9].

Depending on the choice of bare parameters, a non-perturbative formulation of quantum field theories can describe qualitatively different physical situations. A simple example is that the scalar Higgs sector has two phases: the *symmetric phase* where the O(4) symmetry of the scalar fields is explicitly realized and the phase with spontaneous symmetry breaking where the non-zero vacuum expectation value of the field breaks the symmetry. In the presence of Yukawa couplings between the Higgs field and the fermions the phase structure of the theory is presumably more rich. The hopping parameter expansion at strong bare Yukawa coupling shows [9] (see also ref. [10]) that there is a symmetric phase with degenerate massive mirror fermion pairs. A non-zero scalar vacuum expectation value transforms this explicitly mirror symmetric phase into a phase with *spontaneously broken mirror symmetry* where the mirror partners have different masses and are mixed with each other. At weak bare Yukawa-coupling there might be other phases without mirror fermions in the physical spectrum, where the mirror asymmetric perturbation theory with decoupled mirror partners [11] can be applied. If, however, there exist spontaneously broken phases with and without mirror fermions, the question whether nature is in one or in the other phase cannot be answered without an input from experiment.

The presently known phenomenology seems to

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suggest the absence of mirror doubling since no effects of the mirror partners of the known fermion families are observed. Nevertheless, in the phase with spontaneously broken mirror symmetry the natural scale of the mirror fermion masses is the scale of the vacuum expectation value (i.e. a few hundred GeV) and there are possible mixing schemes with three heavy mirror fermion families which agree with all known experiments [12]. The experimental limits on the mirror fermion admixture in the light fermions are, of course, strongest for the first family. They can be inferred from the simultaneous fits of the present data as done in ref. [13]. (The "hermitian mirror fermion model" in ref. [13] corresponds to the model in ref. [12].) For the mixing angles in the first family α_f the upper limits are typically

$$\sin^2\alpha_f \leqslant 0.02-0.05 . \tag{1}$$

The index f stands here to distinguish the members of the first family: f= e, ν_e, u, d. Later on we shall use, however, another notation which follows the conventions of ref. [12]. Namely, $f=Ac$ where $A=1,2$ is the SU(2) weak isospin index and $c=\ell$, q distinguishes leptons and quarks. For instance, $\alpha_{1\ell}$ is in this notation the mixing angle for the electron-neutrino ν_e, etc. The important mechanism of heavy mirror fermion production in high energy ep collisions is given by this mixing. The corresponding vertex and the lowest order Feynman graph for mirror lepton production in electron–proton scattering is shown by fig. 1.

In e^+e^- annihilation (at LEP and SLC) the mirror fermions can also be pair produced via large couplings proportional to $\cos\alpha_f$ if their masses are below $m_Z/2$. If there is a substantial mixing of the order of the upper limits in eq. (1), single mirror fermions can be produced on the Z-peak by the mixing practically up to a mass of M_Z (see also ref. [14]). Therefore, in the present paper we shall concentrate on the mass range above 90 GeV.

Using the same notations as in ref. [12], the production cross section of the mirror electron-neutrino on a u-quark in the proton is

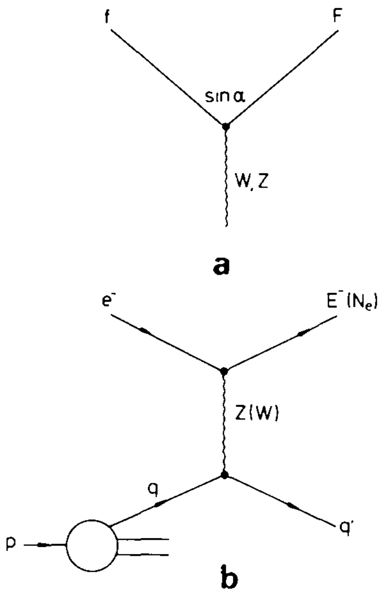

Fig. 1. (a) The mixing vertex between the light fermion (f) and its mirror partner (F). f and F have the same quantum numbers, apart from the exchange of left- and right-hand chiral components. (b) The lowest order Feynman graph in ep scattering for the production of the mirror electron E (electron-neutrino: N_e) through the mixing vertex in (a).

$$\begin{aligned}\frac{d\sigma_{e-u\to N_e d}}{dQ^2} &= \frac{g^4}{512\pi(M_W^2+Q^2)^2}\\ &\times\{[\sin^2(\alpha_{1\ell}-\alpha_{2\ell})+\sin^2(\alpha_{1\ell}+\alpha_{2\ell})]\\ &\times[\cos^2(\alpha_{2q}-\alpha_{1q})+\cos^2(\alpha_{2q}+\alpha_{1q})]\\ &\times[1+(1-y)^2-(M^2/xs)(2-y)]\\ &+4\sin(\alpha_{1\ell}-\alpha_{2\ell})\sin(\alpha_{1\ell}+\alpha_{2\ell})\\ &\times\cos(\alpha_{2q}-\alpha_{1q})\cos(\alpha_{2q}+\alpha_{1q})\\ &\times[1-(1-y)^2-M^2y/xs]\} .\end{aligned} \tag{2}$$

Similarly, the cross section of heavy mirror electron production on u- and d-quarks is ($A=1$ stands for u-quark, $A=2$ for d-quark)

$$\begin{aligned}\frac{d\sigma_{e-q_A\to E-q_A}}{dQ^2} &= \frac{(g^2+g'^2)^2}{2048\pi(M_Z^2+Q^2)^2}\\ &\times\sin^2(2\alpha_{2\ell})[1+\cos^2(2\alpha_{Aq})]\\ &\times[1+(1-y)^2-(M^2/xs)(2-y)] .\end{aligned} \tag{3}$$

Here always zero mass kinematics is assumed, except for the heavy mirror fermion with mass M. x is the

Bjorken variable of the initial parton. Denoting the four-momentum of the electron, mirror-lepton and initial parton, respectively, by p_e, P and xp, the usual kinematical variables are defined as

$$s=(p+p_e)^2\,,\quad q=p_e-P\,,\quad Q^2=-q^2\,,$$

$$y=\frac{p\cdot q}{p\cdot p_e}\,. \tag{4}$$

The kinematical limits are given by

$$1\geqslant x\geqslant x_{\min}\equiv M^2/s\,,\quad 0\leqslant y\leqslant y_{\max}\equiv 1-x_{\min}/x\,. \tag{5}$$

In the production cross sections of mirror electron and mirror electron-neutrino in eqs. (2), (3) three different functions of the mirror mixing angles occur. Since, however, all the angles are small, one can approximate sin α by α and cos α by 1. In this case eq. (2) can be written as

$$\frac{d\sigma_{e^-u\to N_e d}}{dQ^2}\simeq\frac{g^4}{64\pi(M_W^2+Q^2)^2}$$
$$\times[\alpha_{1\ell}^2(1-M^2/xs)$$
$$+\alpha_{2\ell}^2(1-y)(1-y-M^2/xs)]\,. \tag{6}$$

In the same approximation eq. (3) is

$$\frac{d\sigma_{e^-q_4\to E^-q_4}}{dQ^2}\simeq\frac{(g^2+g'^2)^2}{256\pi(M_Z^2+Q^2)^2}\alpha_{2\ell}^2$$
$$\times[1+(1-y)^2-(M^2/xs)(2-y)]\,. \tag{7}$$

The cross sections are dominated by small x- and y-values because of $Q^2=xys$, but a strong peak at small Q^2 characteristic for photon exchange reactions is absent. (Note that the mixing vertex in fig. 1a does not exist for photons.) As a consequence, the total cross section is not sensitive to a cut at small Q^2, which is needed for the applicability of the parton model. (In the following for this cut always $Q^2\geqslant 5$ GeV^2 will be taken and the structure functions of Eichten et al. will be used [15].) The total production cross section and the average transverse momentum for N_e, respectively, E^- production at $\sqrt{s}=314$, 566, 1400 GeV is given in tables 1 and 2. The first energy is typical for HERA with 30 GeV electrons on 820 GeV protons. The second one is a possible HERA upgrade with 40 GeV electrons on 2 TeV protons and the third is in the range of LEP/LHC [16].

Transverse momentum conservation implies that the transverse momentum of the final parton is opposite to the transverse momentum of the produced mirror lepton. The magnitude of both of them is

$$p_T=\sqrt{xys(1-y-M^2/xs)}\,. \tag{8}$$

If in the laboratory frame the electron energy is E_{el} and the proton energy E_{pr}, then the longitudinal momentum of the mirror electron in this frame is

$$P_L=E_{pr}x(y+M^2/xs)-E_{el}(1-y)\,, \tag{9}$$

Table 1
Total production cross section (σ) and average transverse momentum ($\langle p_T\rangle$) of the mirror electron-neutrino in ep collisions at energies $\sqrt{s}=314$, 566, 1400 GeV as a function of the mirror electron-neutrino mass M (in GeV). For simplicity, both mixing angle squared appearing in eq. (6) are assumed here to be 0.02. The cross sections are in 10^{-2} pb, the transverse momenta in GeV.

M	$\sqrt{s}=314$		$\sqrt{s}=566$		$\sqrt{s}=1400$	
	σ	$\langle p_T\rangle$	σ	$\langle p_T\rangle$	σ	$\langle p_T\rangle$
100	31.40	34.92	109.7	51.60	288.28	72.01
120	19.22	32.96	88.45	40.97	261.89	72.55
140	10.99	30.59	70.45	50.03	238.21	72.85
160	5.77	27.98	55.4	48.84	216.81	72.95
180	2.72	25.10	42.94	47.47	197.42	72.89
200	1.11	22.06	32.76	45.93	179.80	72.69
250	–	–	15.31	41.58	141.10	71.76
300	–	–	6.13	36.65	111.79	70.35
350	–	–	1.98	31.23	87.29	68.61
400	–	–	0.444	25.87	67.52	66.61
450	–	–	0.056	19.66	51.59	64.42
500	–	–	0.002	12.94	38.86	62.07

Table 2
The same as table 1, for the mirror electron.

M	$\sqrt{s}=314$		$\sqrt{s}=566$		$\sqrt{s}=1400$	
	σ	$\langle p_T \rangle$	σ	$\langle p_T \rangle$	σ	$\langle p_T \rangle$
100	12.25	35.94	47.33	53.81	139.3	76.25
120	7.35	33.95	37.64	53.30	125.4	77.03
140	4.11	31.56	29.59	52.45	113.05	77.52
160	2.11	28.88	22.98	51.31	102.0	77.80
180	0.97	25.97	17.59	49.94	92.1	77.88
200	0.39	22.83	13.26	48.40	83.3	77.79
250	-	-	6.00	43.90	64.6	77.06
300	-	-	2.32	38.82	49.94	75.76
350	-	-	0.72	33.17	38.38	74.05
400	-	-	0.16	27.33	29.24	72.03
450	-	-	0.02	20.98	22.01	69.81
500	-	-	-	13.42	16.35	67.37

and the struck parton in the final state has a longitudinal momentum given by

$$p'_L = E_{pr} x(1-y-M^2/xs) - E_{el} y . \quad (10)$$

This shows that in most mirror lepton production events there is also a high transverse momentum jet originating from the struck parton. For the high masses considered here the mirror lepton decays predominantly into a light lepton plus a vector boson [12]:

$$N_e \to e^- + W^+, \nu_e + Z, \quad E^- \to e^- + Z, \nu_e + W^-, \quad (11)$$

therefore the final state contains four high transverse momentum leptons or jets. This is the distinguishing experimental signature of heavy mirror lepton production in ep collisions. Once such a signal is observed, the decay distributions have to be studied in detail in order to establish the mirror character of the heavy fermion. The decay channels in eq. (11) have a general mixture of vector and axial-vector couplings depending on the relative magnitude of the mixing angles. The dominantly V + A couplings to W and Z appear in the diagonal terms responsible for the decay of a heavy mirror fermion into another, somewhat lighter, mirror fermion (see, for instance, eq. (6) in ref. [12]).

We have studied the final state distributions by a Monte Carlo program generating the mirror leptons according to eqs. (6), (7). The decays of the mirror lepton into a light lepton and a vector boson were averaged equally over the mirror lepton helicities (small polarization effects were neglected here). Possible background processes for mirror leptons in ep collisions are the second order weak vector boson production (see refs. [17,18] and references therein) and, in case of final states with three jets, QCD multijet production. Both these processes are, however, dominated by photon exchange and hence by low Q^2. The second order weak vector boson production has altogether small cross sections in the order of a few times 10^{-2} pb, even for a low Q^2 cut at 4 GeV^2 [17,19]. The discriminating feature of mirror lepton production is the presence of four large transverse momenta in the final state. In this kinematical range the QCD process is expected to be negligible. (In the leptonic channels the QCD background is, of course, absent.) Fig. 2 shows the distribution of the smallest of the four transverse momenta in the representative case of the $E^- Z$ final state with a mirror electron mass $M = 150$ GeV. As one can see in the figure, in about 85% of the cases all four transverse momenta are larger than 10 GeV, and roughly 50% of the events is above a minimal transverse momentum of 20 GeV.

Since neutrinos can be indirectly detected by the transverse momentum inbalance in the final state, an interesting question is the distribution of the neutrino transverse momentum in the heavy mirror lepton production events. Such a distribution is shown on the example of the $N_e \to e^- + W^+$ final state for a

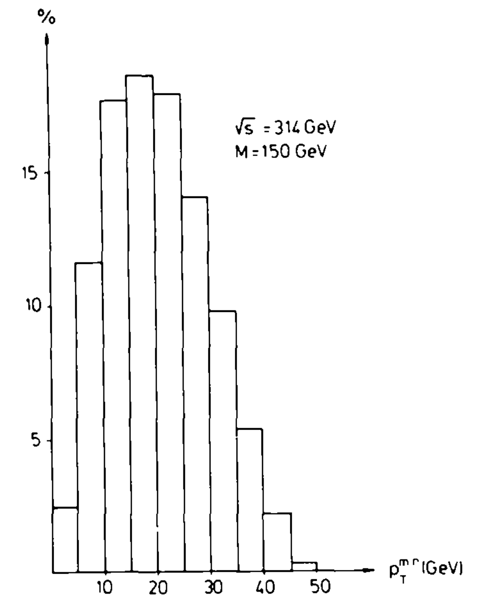

Fig. 2. The distribution of the smallest out of the four transverse momenta of the leptons and/or jets in the final state of the process ep→EZ for a mirror electron mass $M=150$ GeV at $\sqrt{s}=314$ GeV.

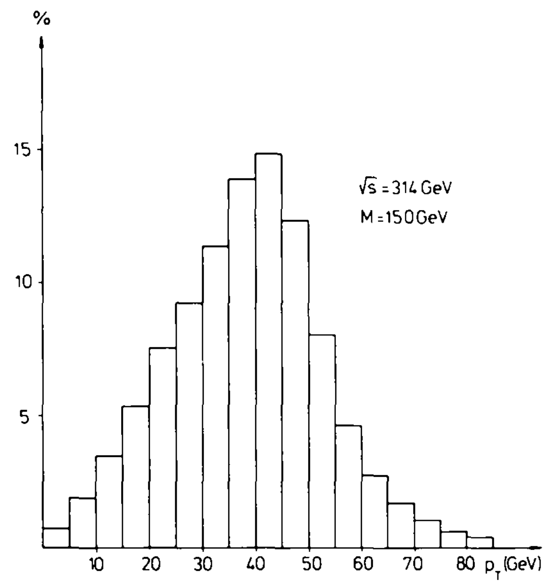

Fig. 3. The inclusive distribution of the neutrino transverse momentum in the process $ep \to eN_e$; $N_e \to \nu_e Z$ or $N_e \to e^- W^+ \to e^- e^+ \nu_e$ for a mirror electron-neutrino mass $M=150$ GeV at $\sqrt{s}=314$ GeV.

mirror neutrino mass $M=150$ GeV in fig. 3. A typical cut at 20 GeV leaves still more than 75% of the events. We have studied several other final state distributions, too. (The Monte Carlo program generating the final states with mirror leptons can be obtained from the authors upon request.)

The conclusion of this Monte Carlo study was that the transverse momenta alone give very distinctive signatures. These informations together with the peaks in the invariant masses are certainly enough to recognize a large fraction of such events above any conventional background. As the tables show, for mixing angles of the order of the present upper limits (1) an integrated luminosity of 100 pb^{-1} at HERA sufficies for the discovery of mirror leptons roughly up to a mass of 200 GeV. The HERA-upgrade could go up to 300–350 GeV, and LEP/LHC up to the unitarity limit for the heavy fermion Yukawa coupling at a mass of about 500 GeV [20]. If the continuum limit of quantum field theories with Yukawa couplings is trivial, then there is also an absolute upper bound for the fermion masses generated by spontaneous symmetry breaking. This bound is for the moment not known, but it may very well be a factor of two below the unitarity limit, similarly to the upper limit for the Higgs-boson mass (see ref. [8] and references therein). In any case, the high energy ep colliders have a good capability to discover the heavy mirror fermions, or at least give important lower limits for their masses and upper limits for their mixing with ordinary fermions.

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