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NEUTRAL HEAVY LEPTON CANDIDATE IN e^+e^- INTERACTIONS

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ABSTRACT

An event of the form $e^+e^- \rightarrow \mu^+\mu^- + (2 \text{ jets})$ recently observed at $\sqrt{s} = 43.45 \text{ GeV}$ is interpreted as production of a pair of neutral heavy leptons N , each with mass $20.5 \pm 1.0 \text{ GeV}/c^2$. Two possibilities are explored: i) the lepton is a weak isodoublet neutrino, produced in pairs by virtual Z^0 decay. In this case, one expects $B(Z^0 \rightarrow N\bar{N}) \approx 5\%$. ii) the lepton is a "right-handed neutrino", produced in pairs via a new vector boson Z_χ . In this case, in one model, the Z_χ must lie between about 50 and 67 GeV/c^2 . More generally, it must be very weakly coupled to ordinary quarks and leptons in order not to conflict with low g^2 neutral-current data. Suggestions are made for further observation of $N\bar{N}$ pairs and other effects of Z_χ in forthcoming e^+e^- and $p\bar{p}$ collisions.

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1. INTRODUCTION

An event has recently been reported [1] of the form

$$e^+ e^- \rightarrow \mu^+ \mu^- + (2 \text{ jets}) \quad (1.1)$$

at $\sqrt{s} = 43.45$ GeV. The small amount of missing energy in this event, and its approximate planar shape, defy conventional explanations. Known processes (including c and b production) have been estimated to contribute 10^{-3} of an event. One suggestion [1] is that the event represents production of a pair $N\bar{N}$ of neutral heavy leptons, which then decay weakly:

$$N^0 \rightarrow \mu^- + (\text{jet})^+ ; \quad \bar{N}^0 \rightarrow \mu^+ + (\text{jet})^- \quad (1.2)$$

In this paper we wish to explore this suggestion further. We shall consider two possibilities: i) N is a sequential weak isodoublet neutrino [2], produced in pairs via a virtual Z^0 , and ii) N is a "right-handed" neutrino, produced in pairs via a new vector boson Z_χ in the 50-67 GeV/c² mass range. Experiments in e^+e^- annihilations above $\sqrt{s} \approx 40$ GeV/c² and in $\bar{p}p$ collisions at CERN and Fermilab should be able to check whether either suggestion is correct in the near future.

In Section 2 we discuss the neutral heavy lepton interpretation of the event. Section 3 treats the consequences of a conventional weak isodoublet assignment of N . The possibility that N is a weak isosinglet, "right-handed" neutrino ($I_{3g} = +\frac{1}{2}$) is studied in Section 4. It is found that an acceptable means of production is via a new vector boson Z_χ . The phenomenology of such a boson is explored in Section 5. It is shown that if such a boson does not mix with the standard Z^0 , if it does not conflict with low-momentum-transfer neutral-current data, and if it couples strongly enough to account for the process (1.1), then it must lie in the mass range of 50-67 GeV/c². The effects of such a boson in $\bar{p}p$ interactions are noted in Section 6. In particular, attention is called to the final state $\mu^+\mu^- + (\text{jets})$, where hints of a signal may be present. Section 7 contains a summary.

2. HEAVY LEPTON INTERPRETATION

We review briefly the event itself. The energies of $(\mu^+, \mu^-, \text{jet}_1, \text{jet}_2)$ are (11.0, 12.6, 10.1, 9.6) GeV. The spatial angle between μ^+ and μ^- is about 120° . The μ^- and jet_1 , and the μ^+ and jet_2 , are both nearly back-to-back: $\theta_{\mu^- \text{jet}_1} \approx 160^\circ$, $\theta_{\mu^+ \text{jet}_2} \approx 154^\circ$. The effective masses of $(\mu^-, \mu^+ \text{jet}_2)$ are $(22.2 \pm 1.6, 19.4 \pm 1.3)$ GeV/c². An average value is 20.5 ± 1.0 GeV/c². There is very little missing energy in the event. The complete four-vectors of the μ 's and jets are given in ref. 1.

It is possible to pair the leptons and jets in different ways, but the effective masses do not come out as close to one another. The nearly planar structure of the event hints at production of a pair of particles near threshold.

No conventional particle is known to decay to $\mu + \text{quark}$ or $\mu + \text{gluon}$. A suggestion has been made [3] that the event represents production of a pair of leptons, each decaying to $\mu + (\text{quark jet})$. This interpretation is being explored further elsewhere. It appears to entail copious production of such particles in $\bar{p}p$ interactions, and thus may be on the verge of being ruled out [3].

A neutral heavy lepton interpretation of a $\mu + \text{jet}$ event requires that it represent the process

$$N \rightarrow \mu^- + u + \bar{d} \quad (\text{or } \bar{u} + d) \quad (2.1)$$

For a conventional β -decay spectrum in this process the muon energy distribution (in the N rest frame) should be

$$\frac{1}{\Gamma} \frac{d\Gamma}{dx} = 2x^2 (3-2x) \quad (2.2)$$

where

$$x = E_\mu / E_\mu^{\text{max}} = 2E_\mu / M_N \quad (2.3)$$

For a *single* N decay, the most likely value of x in eq. (2.2) is 1. The jet mass is related to x by

$$M_{\text{jet}} = M_N (1-x) \quad (2.4)$$

and hence its most likely value is zero. However, on a statistical basis, one expects

$$\langle x \rangle = \int_0^1 x dx \frac{1}{x} \frac{d\Gamma}{dx} = 0.7 \quad (2.5)$$

or

$$\langle M_{jet} \rangle = M_N \sqrt{1 - \langle x \rangle} \approx 0.55 M_N. \quad (2.6)$$

For the one event [eq. (1.1)] the quoted jet masses are (2.4, 4.7) GeV/c² for (j₁, j₂). These are certainly lower than the average expected value [eq. (2.6)], but not at all in conflict with a heavy lepton interpretation. Furthermore, jet masses are notoriously difficult to determine, for example since the assignment of soft particles to jets is not always unique [4].

If $\bar{N}\bar{N}$ is produced nearly at rest with $J_z = \pm 1$ along some axis, as occurs in $e^+e^- \rightarrow \bar{N}\bar{N}$, the favoured direction of emission of the most energetic muon pairs will be back-to-back. To see this, let the lepton which decays to $\mu^+\bar{u}$ have $J_z = +\frac{1}{2}$. The $\bar{u}\bar{d}$ pair will be collinear for maximal muon energy, and will have helicity

$\lambda = -1$. It will thus be emitted preferentially along the $-z$ axis, so the μ^- will favour the $+z$ axis. The lepton which decays to $\mu^+\bar{u}$, assumed also to have $J_z = +\frac{1}{2}$, will then emit the μ^+ along the $-z$ axis, by similar arguments. This argument applies to $\mu^+\mu^-$ pairs. In some models, the lepton N can be a Majorana particle, capable of decaying to either sign of lepton [5]. One then expects also to observe same-sign muon pairs. The most energetic of these will be correlated, rather than anti-correlated, in direction.

The cross-section for the process (1.1) may be compatible with a heavy lepton interpretation. As for the reason why N might decay to μ^- (rather than e^- or τ^-), we must accept this feature as a possible guide to mixing systematics. No bounds on other such decays have been quoted, of course.

3. N AS A "FOURTH-GENERATION" NEUTRINO

The rate for weak isodoublet heavy neutrino (N) pair production in e^+e^- reactions via the standard Z^0 pole is [1]

$$\sigma(e^+e^- \rightarrow N\bar{N}) = \frac{(G_F M_Z^2)^2}{96\pi} \frac{s}{(M_Z^2 - s)^2} \beta(3 + \beta^2)(1 - 4x + 8x^2), \quad (3.1)$$

where $\beta \equiv (1 - 4M_N^2/s)^{1/2}$ is the velocity of N in the e^+e^- c.m.s., and $x \equiv \sin^2 \theta_W$. For $M_N = 20.5$ GeV/c², $\sqrt{s} = 43.45$ GeV, $x = 0.22$, and $M_Z = 94$ GeV/c², we find $\sigma = 0.3$ pb, so approximately one event is expected in the exposure of $\int \mathcal{L} dt = 3.9$ pb⁻¹. However, none of the other three groups at PETRA (JADE, Mark J, TASSO) has reported such an event. One may be then seeing the process (1.1) at a cross-section k or less that of eq. (3.1). This could be because N decays to other things than $\mu + \text{jet}$, or because of an intrinsically lower cross-section.

The Z^0 should decay to $N\bar{N}$ with a rate

$$\Gamma(Z^0 \rightarrow N\bar{N}) = \frac{G_F^2 M_Z^3}{12\pi\sqrt{2}} \left(1 - \frac{M_N^2}{M_Z^2}\right) \left(1 - \frac{4M_N^2}{M_Z^2}\right)^{1/2}, \quad (3.2)$$

or $B(Z^0 \rightarrow N\bar{N}) \approx 5\%$ for $M_N = 20.5$ GeV/c², $\Gamma_Z = 2.8$ GeV. The decays $Z^0 \rightarrow e^+e^-$ [6,7] and $Z^0 \rightarrow \mu^+\mu^-$ [6,8,9] have been observed. Each is expected to be about 3% of all Z^0 decays. Thus if N is a "standard" neutrino, it should be seen in Z^0 decays in these same experiments.

A preliminary report of $\bar{p}p$ events at $\sqrt{s} = 540$ GeV with $\mu^+ + \mu^- + \text{jets}$ has been presented [9]. One such event has a mass combination of $\mu^+\mu^- + (\text{some jets})$ compatible with origin from a Z^0 . However, it also could have come from $t\bar{t}$ or $W + t\bar{b}$ production, and thus be due to more "conventional" physics.

The question still can remain open whether the N is a standard "fourth-generation" lepton in all respects, coupled to $\bar{u}$ left-handedly. If so, in the decay $N \rightarrow \mu^+\bar{u}$, not only the μ^- but also the u will have a spectrum $d\Gamma/dx \propto x^2(3 - 2x)$, where $x = E/E_N^{\text{max}}$, E measured in the N rest frame. The $\bar{d}$ will have a somewhat softer spectrum $d\Gamma/dx \propto x^2(1 - x)$. It is prevented from having the maximum

energy by helicity arguments. Another possibility is that N is a "mirror fermion" [10], whose *right-handed* helicity state belongs to a weak isodoublet with a heavier lepton $\bar{M}^-$. The decay of N then proceeds via $\bar{M}^- \mu^-$ mixing, and leads to a *right-handed* μ^- . In this case $d\Gamma/dx \propto x^2(1-x)$, while $d\Gamma^{\bar{d}}/dx \propto x^2(3-2x) (\propto d\Gamma^{\mu^-}/dx)$. It may be possible to distinguish between the "ordinary" and "mirror" fermion cases by inspecting the charge of the leading particle opposite the muon in the decays (1.2). For an ordinary fermion, in $N \rightarrow \mu^- \bar{u}$ the leading hadron is more likely to be a fragment of the u , while for a mirror fermion it is more likely to be a fragment of $\bar{d}$.

4. N AS A "RIGHT-HANDED" NEUTRINO

If the event of ref. 1 is confirmed by further similar events but the decay $Z^0 \rightarrow \bar{N}N$ is not seen at the 5% branching ratio level, there exists at least one other possible interpretation in terms of a neutral heavy lepton. The event could be a pair of weak isoscalar "right-handed neutrinos". In order for the process (1.1) to occur with the observed cross-section, a new production mechanism must be sought. The limits on mixing of ordinary isodoublet neutrinos with "inert" isosinglet ones are rather stringent [11,12], particularly for muon neutrinos, for which the square of the mixing amplitude is expected to be less than a per cent.

One possibility for $e^+e^- \rightarrow \bar{N}N$ would involve exchange of a right-handed W , coupling with strength $g_R = g_L$ to eN . The corresponding cross-section is

$$\sigma(e^+e^- \rightarrow \bar{N}N; W_R \text{ exchange}) = \frac{(G_F M_W)^2}{8\pi} \frac{s}{M_{W_R}^2} \beta(3+\beta^2), \quad (4.1)$$

which is less than 0.02 pb for $M_{W_R} \geq 300 \text{ GeV}/c^2$. In fact, it is likely that $M_{W_R} \geq 1-2 \text{ TeV}/c^2$ [13], so eq. (4.1) could not account for the level of production implied in the event of ref. 1.

Another possible mechanism for $e^+e^- \rightarrow \bar{N}N$ (N = right-handed neutrino) is via a new neutral intermediate vector boson. In Section 4 we shall examine in detail

the phenomenology of one such boson. Here we wish to limit ourselves to more general remarks.

The effective squared coupling constant of the Z^0 is

$$\frac{g_L^2 + g'^2}{4\pi} \equiv \frac{8 M_Z^2 G_F}{4\pi \sqrt{2}} = 4.62 \times 10^{-2} \approx 1/22 \quad (4.2)$$

Here $g_L = e/\sin \theta$ and $g' = e/\cos \theta$ are the $SU(2)_L$ and $U(1)_Y$ coupling constants of the standard electroweak theory. Let the new gauge boson Z_χ have a mass M_{Z_χ} and gauge coupling g_χ . In order that it not disturb low- q^2 neutral-current phenomenology appreciably, we shall demand

$$\frac{g_\chi^2}{g_L^2 + g'^2} \frac{M_Z^2}{M_{Z_\chi}^2} \lesssim \mathcal{O}(10\%) \quad (4.3)$$

At the same time, in order that one reproduce at least 10% of the cross-section (3.1) by exchange of the boson Z_χ in the s channel, we require ($\sqrt{s} = 43.45 \text{ GeV}$)

$$\left[\frac{g_\chi^2}{g_L^2 + g'^2} \frac{M_Z^2 - s}{M_{Z_\chi}^2 - s} \right]^2 \geq \mathcal{O}(10\%) \quad (4.4)$$

We require this in order that the event (1.1) not have been observed merely by chance. Combining eqs. (4.3) and (4.4), we find $M_{Z_\chi} \lesssim \mathcal{O}(50 \text{ GeV})$, and $g_\chi^2/4\pi \lesssim 1/750$. The new boson must be *relatively light and weakly coupled*. At the same time it must lie above about 49 GeV, or its effects would have been seen in present e^+e^- experiments [14]. In one specific model to be discussed in Section 5, eqs. (4.3) and (4.4) are replaced by quantitative estimates, and one finds an allowed range $50 \leq M_{Z_\chi} \leq 67 \text{ GeV}/c^2$.

There are at least two contexts in which a light "extra Z " has been suggested. The first is one in which a new $U(1)$ is associated with spontaneous supersymmetry breaking [15]. The boson coupled to this $U(1)$ has indeterminate mass and coupling strength, but from these parameters one can learn further interesting quantities such as the gravitino mass. Such a boson of mass $\approx 50 \text{ GeV}/c^2$ would imply a very light gravitino ($\lesssim 10^{-5} \text{ eV}$) [15].

A second potential source of a very light "extra Z " (" Z_X ") comes if we attempt to gauge not only weak isospin I_L and hypercharge Y_W , but also I_{3R} or, equivalently, $B-L = (\text{baryon number}) - (\text{lepton number})$ [16]. Phenomenological analyses have tended to require that $M_{Z_X} \geq 200 \text{ GeV}/c^2$ [17-25]. In these, the coupling constant g_X was estimated to satisfy $1/90 \leq g_X^2/4\pi \leq 1/60$ on the basis of various versions of an $SO(10)$ grand unified theory (GUT) [18]. These bounds are about a factor of 10 larger than the values of $g_X^2/4\pi$, being considered here. Hence it is not surprising that the possibility of a very light Z_X was not considered seriously in such analyses, though it was mentioned in passing in ref. 18.

In the next section we give one example of a light Z_X which can account for the process (1.1) without appreciably disturbing low- q^2 neutral-current phenomenology.

5. PHENOMENOLOGY OF A LIGHT UNMIXED Z_X BOSON

5.1 Formalism

We first review the motivation for a relatively light neutral gauge boson besides the Z^0 [16,19].

Normally one writes

$$Q = I_{3L} + \frac{Y_W}{2} \quad (5.1)$$

and gauges both I_{3L} and Y_W . The physical photon and Z^0 are mixtures of gauge bosons coupling to I_{3L} and Y_W . A more symmetric form is

$$Q = I_{3L} + I_{3R} + \frac{B-L}{2} \quad (5.2)$$

If one gauges I_{3L} , I_{3R} , and $B-L$ separately and demands the absence of anomalies in all currents, a) a right-handed neutrino N must exist corresponding to each left-handed neutrino ν (we ignore more complicated possibilities), and b) there is a unique combination of I_{3L} , I_{3R} , and $B-L$ orthogonal to that in γ and Z^0 , to which a new boson Z_X couples. In the absence of mixing between Z_X and γ or Z^0 , this charge is [17-19]

$$Q_X \equiv \frac{1}{\sqrt{10}} [5I_{3R} + 3(I_{3L} - Q)], \quad (5.3)$$

where we have eliminated $B-L$ via eq. (5.2). The normalization chosen in eq. (5.3) is such that $3Q_X^2 = 5I_{3L}^2 = 5I_{3R}^2 = 2$ for a generation of quarks and leptons (with the right-handed neutrino included). The values of Q_X for members of a generation are summarized in Table 1. Note that N has a large Q_X charge.*

The interaction Lagrangian in the absence of mixing between Z^0 and Z_X is

$$\begin{aligned} \mathcal{L}_{int} = & -e \bar{\psi} Q \not{A} \psi - \sqrt{g_L^2 + g'^2} \bar{\psi} (I_{3L} - Q_X) \not{Z}^0 \psi \\ & - g_X \bar{\psi} Q_X \not{Z}_X \psi \end{aligned} \quad (5.4)$$

Now, normally the Z^0 and Z_X would couple to linear combinations of the above charges. As mentioned, most phenomenological analyses [17-25] then predict the Z^0 to be displaced very slightly downward in mass from its value in the standard model [26]

$$M_Z = M_0 \equiv 93.8^{+2.4}_{-2.2} \text{ GeV}/c^2, \quad (5.5)$$

and the Z_X to lie above $\sim 200 \text{ GeV}/c^2$. However, with very small g_X^2 , as noted briefly in Ref. 18, it is possible for a Z_X to be relatively light, with the standard Z^0 displaced slightly upward in mass.

The observed values are

$$M_Z = \begin{cases} 95.6 \pm 1.4 \pm 2.9 \text{ GeV}/c^2 & (\text{041 [6]}) \\ 92.7 \pm 1.7 \pm 1.4 \text{ GeV}/c^2 & (\text{042 [7]}) \end{cases}, \quad (5.6)$$

which we shall interpret as $94 \pm 3 \text{ GeV}/c^2$. Comparing this value with eq. (5.5), and anticipating a modest increase in accuracy, we expect that it will be possible

*) Note that Q_X values are the same for each member of a given $SU(5)$ representation. The charge Q_X is that associated with the $U(1)$ in $SO(10) \rightarrow SU(5) \times U(1)$. The fermions in Table 1 belong to a single 16-plet of $SO(10)$.

to show that M_{Z^0} lies within 3 GeV/c² of M_0 in the near future. For simplicity, we shall show that a choice of Higgs bosons is possible such that Z_χ does not mix at all with the standard Z^0 . It is important to realize, however, that even a shift of Z^0 by as little as 3 GeV/c² allows considerable freedom in Z^0 - Z_χ mixing.

The most general neutral Higgs bosons we shall consider have $|I_{3L}| \leq \frac{1}{2}$, $|I_{3R}| \leq \frac{1}{2}$. They may be labelled by I_{3L} , I_{3R} , and $(B-L)/2$ as

$$\phi_2^{u,d} \sim (\pm \frac{1}{2}, \mp \frac{1}{2}, 0) \quad (\langle \phi_2^{u,d} \rangle \equiv v_2^{u,d}); \quad (5.8)$$

$$h_2^{u,d} \sim (\pm \frac{1}{2}, 0, \mp \frac{1}{2}) \quad (\langle h_2^{u,d} \rangle \equiv w_2^{u,d}); \quad (5.9)$$

$$h_1^{u,d} \sim (0, \pm \frac{1}{2}, \mp \frac{1}{2}) \quad (\langle h_1^{u,d} \rangle \equiv w_1^{u,d}). \quad (5.10)$$

The masses of gauge bosons arise from the kinetic part of the Lagrangian,

$$\mathcal{L}_K = (D^\mu \phi^i)^\dagger (D_\mu \phi^i) + (D^\mu h_j^i)^\dagger (D_\mu h_j^i), \quad (5.11)$$

where

$$D^\mu \equiv \partial^\mu + i(g_L \vec{I}_L \cdot \vec{W}^\mu + g' \frac{Y}{2} B^\mu + g_\chi Q_\chi Z_\chi^\mu). \quad (5.12)$$

Let us define

$$V_2^2 \equiv v_2^{u^2} + v_2^{d^2} \quad (5.13)$$

$$W_2^2 \equiv w_2^{u^2} + w_2^{d^2} \quad (5.14)$$

$$W_1^2 \equiv w_1^{u^2} + w_1^{d^2} \quad (5.15)$$

Then the boson mass matrix is

$$\frac{1}{2} \mathcal{M}^2 = \frac{1}{4} \begin{bmatrix} g^2(V_2^2 + W_2^2) & -gg'(V_2^2 + W_2^2) & \frac{gg_\chi}{\sqrt{10}}(3W_2^2 - 2V_2^2) \\ -gg'(V_2^2 + W_2^2) & g'^2(V_2^2 + W_2^2) & -\frac{g'g_\chi}{\sqrt{10}}(3W_2^2 - 2V_2^2) \\ \frac{gg_\chi}{\sqrt{10}}(3W_2^2 - 2V_2^2) & -\frac{g'g_\chi}{\sqrt{10}}(3W_2^2 - 2V_2^2) & \frac{g^2}{10} \left(\frac{2}{5} V_2^2 + \frac{9}{10} W_2^2 + \frac{5}{2} W_1^2 \right) \end{bmatrix} \quad (5.16)$$

Special cases of this matrix have been analysed in refs. [18] ($V_2 = 0$) and [21] ($W_2 = 0$), and more general discussions also exist [24,25]. The choice $V_2 = 0$ removes all effects of the new boson on $g^2 = 0$ neutrino neutral-current interactions [18]. When $W_2 = 0$, the additional effective neutral-current Hamiltonian is purely vector-like. In both cases, the magnitude of g_χ^2 does not enter into low- q^2 neutral-current phenomenology, and one finds

$$W_1^2/W_2^2 \geq 3 \quad \text{for } V_2 = 0 \quad [13] \quad (5.17)$$

$$W_1^2/V_2^2 \geq 7 \quad \text{for } W_2 = 0 \quad [21]. \quad (5.18)$$

The masses of Z^0 and Z_χ do depend on g_χ^2 . It is convenient to define

$$\hat{g}^2 \equiv \frac{g_\chi^2}{g_L^2 + g'^2} \quad (5.19)$$

An example with $V_2 = 0$ is shown in Fig. 1. There exists a regime with very small $\hat{g}^2$, in which one Z is very close in mass and coupling to the standard one, while the other is lighter. Its couplings tend to be rather distorted from those of the unmixed Z_χ by mixing with the standard Z .

A complete discussion of the compatibility of the parameters in eq. (5.16) with low-energy neutral-current phenomenology, when one eigenvalue is within

3 GeV/c² of M_0 and the other is fairly light, would be worthwhile but is beyond the scope of the present paper^{*)}. Here we shall merely note that the choice

$$3 W_2^2 = 2 V_2^2 \quad (5.20)$$

decouples the Z_χ from the standard Z^0 entirely. No deviation of the Z^0 mass from the standard model prediction then occurs. The discussion then simplifies tremendously, and allows us to refine the estimates (4.3) and (4.4) in the context of a particular model. We shall try to indicate where particularly model-dependent effects occur.

5.2 Low-q² neutral-current results

The term proportional to g_χ in the Lagrangian (5.4) leads to an additional contribution to a number of low-q² neutral-current parameters, which have been defined elsewhere. All of these are proportional to the quantity

$$y \equiv g^2 M_0^2 / M_{Z_\chi}^2 \quad (5.21)$$

For notation we refer the reader to refs. [27,28] and more briefly to refs. [18] and [21]. The quantities to be fitted are displayed in table 2. [We shall discuss electroweak asymmetries in $e^+e^- \rightarrow (\mu^+\mu^-, \text{hadrons})$ presently.] The data come from the compilation of ref. [27] and refs. [29-34].

A simultaneous fit to the low-q² parameters in table 2 yields the central values $x = 0.254$, $y = 0.04$, with $\chi^2 = 5.3$ for 7 degrees of freedom. The contour of $\Delta\chi^2 = 1$ is shown in fig. 2. The coupling strength parameter y satisfies the bound

$$y \equiv \frac{g_\chi^2}{g_L^2 + g'^2} \frac{M_0^2}{M_{Z_\chi}^2} < 0.112, \quad (5.22)$$

which is saturated for $x = 0.268$. For $y = 0$, values of x between 0.23 and 0.265 are acceptable. For the present model, x and y are strongly correlated. This is

*) A further variation on the present model, studied to some extent in refs. [17-25], is to treat the coupling constants for I_{3R} and $B-L$, rather than those Y and Q_χ , separately. The limit $g^2 \rightarrow 0$ would then correspond to very precise relations between g_R and g_{B-L} , however.

not always so for other versions, such as that studied in ref. [18] in which neutrino neutral-current deep inelastic scattering is unaffected by a Z_χ .

5.3 Electroweak asymmetries in e^+e^- reactions

Electroweak parameters h_{VV}^f and h_{AA}^f contribute to the differential cross-section for $e^+e^- \rightarrow f\bar{f}$ in the form

$$\frac{d\sigma}{ds} (e^+e^- \rightarrow f\bar{f}) = \frac{\alpha^2}{4s} Q_f^2 N_c \times \left[(1 + 2h_{VV}^f) (1 + \cos^2\theta) + 4h_{AA}^f \cos\theta \right], \quad (5.23)$$

where N_c is the number of colours (1 for a lepton, 3 for a quark), and

$$\rho \equiv -\sqrt{2} G_F s / e^2 \quad (5.24)$$

We shall neglect the effects of the Z^0 pole, but not those of the Z_χ pole, in γ - Z_χ interference in e^+e^- reactions up to $\sqrt{s} \approx 45$ GeV. A convenient parameter to describe the enhancement due to the Z_χ pole is the ratio

$$E \equiv M_{Z_\chi}^2 / (M_{Z_\chi}^2 - s) \quad (5.25)$$

We then find

$$h_{VV}^\mu = \left(-\frac{1}{2} + 2x\right)^2 + \frac{2}{5} y E \quad (5.26)$$

$$h_{AA}^\mu = \frac{1}{4} \left(1 + \frac{2}{5} y E\right) \quad (5.27)$$

$$h_{VV}^u = \left(-\frac{1}{2} + 2x\right) \left(\frac{1}{2} - \frac{4}{3} x\right) / \left(-\frac{2}{3}\right) \quad (5.28)$$

$$h_{AA}^u = -\frac{1}{4} \left(1 + \frac{2}{5} y E\right) \quad (5.29)$$

$$h_{VV}^d = \left[\left(-\frac{1}{2} + 2x\right) \left(-\frac{1}{2} + \frac{2}{3} x\right) - \frac{2}{3} y E \right] / \left(-\frac{1}{3}\right) \quad (5.30)$$

$$h_{AA}^d = \frac{1}{4} \left(1 + \frac{2}{5} y E \right). \quad (5.31)$$

We concentrate on two observables which are likely to give accurate data at the highest PETRA energies: h_{VV}^μ and the contribution of h_{VV}^d to $R \equiv \sigma(e^+e^- \rightarrow \text{hadrons}) / \sigma(e^+e^- \rightarrow \mu^+\mu^-)$. (The contributions of d, s, b are assumed identical).

In Fig. 3 we plot h_{VV}^μ and ΔR versus $M_{Z_\chi}^\mu$ for the choice $x = \frac{1}{4}$, which leads to $h_{VV}^i = 0$ ($i = \mu, u, d$) in the absence of a Z_χ contribution. We choose $\sqrt{s} = 44$ GeV, for which a large amount of PETRA data has been accumulated. As an example, if a bound $h_{VV}^\mu \lesssim 0.1$ or $\Delta R \lesssim 0.2$ can be achieved ($h_{VV}^\mu \lesssim 0.06$ was established at $\sqrt{s} = 34$ GeV [35]*), a bound on y stronger than that in eq. (5.22) will result for $M_{Z_\chi} \lesssim 59$ GeV/c².

Forward-backward asymmetries, described by h_{AA}^i , are less sensitive to the effects of Z_χ exchange with the very weak couplings proposed here. Limits of $h_{VV}^\mu \lesssim 0.1$ correspond to less than 10% effects on h_{AA}^i for any fermion species.

5.4 Effects on $e^+e^- \rightarrow N\bar{N}$

Despite the very small value of $g_\chi^2/4\pi$, it is possible for a light Z_χ to contribute appreciably to the process (1.1). With the Lagrangian (5.4), the cross-section of interest is

$$\begin{aligned} \sigma(e^+e^- \rightarrow Z_\chi^{\text{virtual}} \rightarrow N\bar{N}) &= \frac{(g_\chi^2)^2}{48\pi} \frac{5}{(M_{Z_\chi}^2 - s)} \\ &\quad \times \beta \left\{ \frac{3 + \beta^2}{4} \right\} \left\{ (Q_\chi^{eL})^2 + (Q_\chi^{eR})^2 \right\} \left\{ (Q_\chi^{NR})^2 \right\}, \end{aligned} \quad (5.32)$$

where β is as in eq. (3.1). The charges Q_χ are given in table 1. Let us assume that the cross-section (5.32) at $\sqrt{s} = 43.45$ GeV is at least 0.026 pb, corresponding

*) This is our interpretation of the bound $x \geq 0.13$ quoted in ref. [35].

to a 1 in 10 chance for the CELLO detector to have observed the event. Then we find

$$\frac{g_\chi^2}{4\pi} \frac{1}{M_{Z_\chi}^2 - s} \geq 9.1 \times 10^{-7} \text{ GeV}^{-2}, \quad (5.33)$$

or, combining this estimate with eq. (5.22),

$$0.112 \geq y \geq 0.173 \left[1 - \left(\frac{43.45 \text{ GeV}}{M_{Z_\chi}} \right)^2 \right]. \quad (5.34)$$

This limit is shown as the heavy lines on the curves for h_{VV}^μ and ΔR in fig. 3, corresponding to excluded values. The bound in eq. (5.34) can only be satisfied for

$$M_{Z_\chi} \leq 73.4 \text{ GeV}/c^2. \quad (5.35)$$

Thus a Z_χ which is too heavy cannot contribute enough to the process (1.1) for it to have been observed other than by chance.

The region of y and M_{Z_χ} excluded by eq. (5.34) is bounded by the solid lines in fig. 4. Also shown is the contour for h_{VV}^μ ($\sqrt{s} = 34$ GeV) = 0.06. We interpret the data of ref. [35] as excluding a larger value. This narrows the choices of y and M_{Z_χ} further, restricting

$$M_{Z_\chi} \leq 67 \text{ GeV}/c^2. \quad (5.36)$$

For illustration, we have shown also the contour for h_{VV}^μ ($\sqrt{s} = 44$ GeV) = 0.08.

Since h_{VV}^μ scales as y , we see that for all allowed values of M_{Z_χ} , one expects

$$h_{VV}^\mu \geq 0.07 \quad (5.37)$$

$$\Delta R \geq 0.14 \quad (5.38)$$

almost independently of the Z_χ mass in this model*). Equation (5.34) entails at least a 5% reduction in the expected cross-section for $e^+e^- \rightarrow \mu^+\mu^-$, relative to

*) At $\sqrt{s} = 43.45$ GeV the predicted lower bounds for h_{VV}^μ and ΔR would be strictly independent of M_{Z_χ} .

that expected for single-photon exchange. This should be no problem to observe, if accuracy of lower-energy data is any guide [35].

We now turn to possible signatures for Z_χ and heavy leptons in $\bar{p}p$ collisions.

6. EFFECTS OF A Z_χ (50-67 GeV/c²) ON $\bar{p}p$ INTERACTIONS

The production and decays of Z_χ in $\bar{p}p$ collisions may be estimated straightforwardly. First we show in table 3 the expected branching ratios for Z_χ of various masses coupling via the charges of table 1 to three flavours of neutrinos and charged leptons, one flavour of $\bar{N}\bar{N}$, two of $Q = 2/3$ quark (we assume $2m_t > M_{Z_\chi}$), and three of $Q = -1/3$ quark. Note the small branching ratio to $u\bar{u}$ and the large $\bar{N}\bar{N}$ mode. Both these features are very sensitive to any mixing with the Z^0 , and may not be present to the degree shown in table 3.

The cross-sections for production of gauge bosons in Drell-Yan processes

$A + B \rightarrow Z + \dots$ may be expressed as

$$s \frac{d\sigma}{dy} (A+B \rightarrow Z+\dots) = \frac{4\pi^2}{3M_Z^2} \left[\{ u_A(x_1) \bar{u}_B(x_2) + \bar{u}_A(x_1) u_B(x_2) \} \Gamma_{u\bar{u}}^Z + (u \rightarrow d) \right], \quad (6.1)$$

where y is the rapidity, $x_1 = (M/\sqrt{s})e^y$, $x_2 = (M/\sqrt{s})e^{-y}$, u_A is a quark distribution function for u quarks in hadron A , and $\Gamma_{u\bar{u}}^Z$ is the partial decay rate of Z into $u\bar{u}$. For the standard Z , $(\Gamma_{u\bar{u}}^Z, \Gamma_{d\bar{d}}^Z) = (317, 406)$ MeV, when $M_{Z^0} = 93.8$ GeV/c², $x = \sin^2 \theta_W = 0.22$. For the Z_χ , we predict values which may be inferred from table 3.

We calculate both the cross-section for Z^0 production and the *minimum* cross-sections for Z_χ production at each mass, based on the lower bounds on y implied by eq. (5.34). The results are shown in table 4. We have used here structure functions of ref. [36], based on CDHS quark and gluon distributions extrapolated to large Q^2 with a QCD scale $\Lambda = 0.29$ GeV. As an example, at $\sqrt{s} = 540$ GeV for $M_{Z_\chi} = 55$ GeV/c² we expect

$$\sigma(\bar{p}p \rightarrow Z_\chi(55) \rightarrow e^+e^-) = 5-9 \text{ pb} \quad (6.2)$$

$$\sigma(\bar{p}p \rightarrow Z_\chi(55) \rightarrow N\bar{N}) = 7-12 \text{ pb}, \quad (6.3)$$

where the lower values correspond to $y = y_{\min}$ and the higher to the bound (5.22).

The corresponding prediction for $Z^0(94)$ is 31 pb, to be compared with the experimental numbers

$$\left\{ \begin{array}{l} 71 \pm 24 \pm 13 \text{ pb} \\ \cup A1 [6] \end{array} \right\} \quad \left(\begin{array}{l} 4 \text{ events:} \\ \cup A1 [6] \end{array} \right) \quad (6.4)$$

$$\sigma(\bar{p}p \rightarrow Z^0(94) \rightarrow e^+e^-) = \left\{ \begin{array}{l} 110 \pm 40 \pm 20 \text{ pb} \\ \cup A2 [7] \end{array} \right\} \quad \left(\begin{array}{l} 8 \text{ events:} \\ \cup A2 [7] \end{array} \right). \quad (6.5)$$

Thus we might have expected to see a $Z_\chi \rightarrow e^+e^-$ decay and an instance or two of $Z_\chi \rightarrow N\bar{N}$ in the total present sample.

There is no indication in either UA1 or UA2 data of the decay $Z_\chi \rightarrow e^+e^-$.

In the mass distribution of

$$\bar{p}p \rightarrow \mu^+ + \mu^- + (\text{jets}) + \dots, \quad (6.6)$$

the effective mass distribution of $\mu^+ + \mu^- + (\text{jets})$ does contain events in the 50-70 GeV/c² range [8,9]. At least some of these could come from

$$\bar{p}p \rightarrow Z_\chi + \dots \rightarrow N\bar{N} + \dots \quad \left\{ \begin{array}{l} \rightarrow \mu + \text{jet}(s) \\ \rightarrow \mu + \text{jet}(s) \end{array} \right\} \quad (6.7)$$

However, an important source of the reaction (6.6), aside from any possible heavy lepton, is the production of pairs of heavy quarks ($c\bar{c}$, $b\bar{b}$, ...), followed by semileptonic decays. For $c\bar{c}$ and $b\bar{b}$ pairs, the events in the 50-70 GeV/c² range of course should be only the tail of a distribution with much lower average effective mass. Production of t quarks (either via $t\bar{t}$ or W decays) also provides a potentially important background to the process (6.7).

If the events (6.6) are due to semileptonic decays of quarks, one should see identical behaviour in the $(e^+ + e^- + \text{jets})$ and $(\mu^+ + e^- + \text{jets})$ spectra. A heavy lepton, by contrast, could easily favour the muonic decay channel, as has been found in a particular model [11].

We are unable to account for $Z^0 \rightarrow e^+e^-\gamma$ or $Z^0 \rightarrow \mu^+\mu^-\gamma$ events [7-9] by means of a Z_χ , within the context of a gauge theory.

If the N indeed is a "right-handed neutrino", there are still two distinct possibilities for its behaviour. If it is a Majorana neutrino, it may be able to decay to either sign of lepton [5]. There could then be $\mu^+\mu^+$ + jet events in $p\bar{p}$ collisions. At least one such event $(\mu^+\mu^-)$ has been seen so far [8,9]. However, it also has a natural interpretation in terms of $W^- \rightarrow \bar{e}b$ decay.

The N could also be a Dirac neutrino (if an "inert" two-component companion were supplied to make it massive). A model of this type, in which one N naturally mixes with ν_μ , has been discussed in ref. [11]. In this case the mixing amplitude is expected to be about $|U_{N\mu}| \approx 10^{-3}$, and the lifetime can be estimated by standard means [12] to be about 10^{-12} s. Such a Dirac particle gives rise to "right-sign" primary leptons in its decay: $N \rightarrow \mu^- + \dots, \bar{N} \rightarrow \mu^+ + \dots$.

7. SUMMARY

We have discussed the possibility that pair production of a neutral heavy lepton N of mass $20.5 \pm 1.0 \text{ GeV}/c^2$ is being observed in e^+e^- annihilations. Two alternatives were suggested for this lepton: i) a weak isodoublet, produced through a virtual Z^0 , and ii) a new "right-handed" version, produced through a new vector boson " Z_χ " lighter than the Z. If the first alternative is correct, one should see $Z^0 \rightarrow N\bar{N}$ with a 5% branching ratio.

One model for the new boson Z_χ in which it does not mix with the standard Z was discussed extensively for illustrative purposes. Such a boson can be expected to affect the cross-section for $e^+e^- \rightarrow \mu^+\mu^-$, reducing it by at least 5% at $\sqrt{s} = 44 \text{ GeV}$, and the value of R, raising it by at least 0.14 at $\sqrt{s} = 44 \text{ GeV}$. Effects at higher $\sqrt{s}$ will of course depend sensitively on the mass of the boson.

This mass must be between 50 and 67 GeV/c^2 in the present model, if it is to contribute to right-handed heavy lepton production in reaction (1.1).

The production of Z_χ in $p\bar{p}$ collisions has been estimated. Its e^+e^- decay should be visible in the next series of experiments at CERN. It is possible that $\mu^+\mu^-$ + (jets) events are already candidates for $Z_\chi \rightarrow N\bar{N}$. The decay $Z_\chi \rightarrow N\bar{N}$ might not contribute to e^+e^- + (jets).

The coupling of Z_χ to ordinary matter must be quite weak in order for it to affect $e^+e^- \rightarrow N\bar{N}$ at $\sqrt{s} = 43.45 \text{ GeV}$ without having been noticed elsewhere. The weakness of this coupling is difficult to understand on the basis of conventional GUTs, but has been discussed previously in certain versions of spontaneously broken supersymmetry [15].

Our quantitative conclusions have relied on the assumption, made for simplicity, that Z_χ mixes very little with the ordinary Z. We then find

$$\frac{\Gamma(Z_\chi \rightarrow N\bar{N})}{\Gamma(Z_\chi \rightarrow e^+e^-)} = \frac{5}{2} \left(1 - \frac{M_N^2}{M_{Z_\chi}^2}\right) \left(1 - \frac{4M_N^2}{M_{Z_\chi}^2}\right)^{1/2}, \quad (7.1)$$

which is rather large. This ratio can be rather sensitive to the precise choice of Higgs bosons: larger in some models, smaller in others. A sweep of the e^+e^- energy range above the maximum obtained so far, 46.78 GeV [37], would settle in a model-independent way the question of whether Z_χ exists below the Z^0 . The typical widths one might expect for a Z_χ coupled with g^2 ten or more times smaller than that of the Z^0 are still in the 10-100 MeV range, and predicted leptonic branching ratios are several per cent, so a resonant peak will be hard to miss.

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Table 1

Charges Q_χ for coupling of an unmixed gauge boson Z_χ to left-handed quarks and leptons. For right-handed fermions, reverse the sign of Q_χ .

$2\sqrt{10} Q_\chi$	Left-handed fermions
3	$\bar{d}, e^-, \nu_e$
-1	$d, u, \bar{u}, e^+$
-5	$\bar{N}_e$

Table 2

Low- q^2 neutral-current parameters to be fitted.
Here $x \equiv \sin^2 \theta_w$, $y = g^2 M_0^2 / M_{Z_\chi}^2$.

Process [Ref.]	Parameter	Theoretical expression	Value
Neutrino neutral-current deep inelastic scattering [27]	$\varepsilon_L(u)$	$\frac{1}{2} - \frac{2}{3}x - \frac{3}{20}y$	0.340 ± 0.033
	$\varepsilon_R(u)$	$-\frac{2}{3}x + \frac{3}{20}y$	-0.179 ± 0.019
	$\varepsilon_L(d)$	$-\frac{1}{2} + \frac{1}{3}x - \frac{3}{20}y$	-0.424 ± 0.026
	$\varepsilon_R(d)$	$\frac{1}{3}x - \frac{9}{20}y$	-0.017 ± 0.058
Polarized electron-deuteron deep inelastic scattering [29]	$\tilde{\alpha} + \frac{1}{3}\tilde{\gamma}$	$-1 + \frac{20}{9}x + \frac{4}{15}y$	-0.60 ± 0.16
	$\tilde{\beta} + \frac{1}{3}\tilde{\delta}$	$-1 + 4x - \frac{4}{5}y$	0.31 ± 0.51
Atomic P violation: Cs [30,31] Tl [32] Bi [33,34]	Q_W	$-(23 + 220x) + 169y$	-57 ± 29
	Q_W^{ν}	$-(42 + 324x) + 262y$	-155 ± 63
	Q_W^{ν}	$-(43 + 332x) + 268y$	-126 ± 45^a

a) Our estimate of value and error for average of two experiments.

Table 3

Branching ratios B of an unmixed Z_χ , in per cent. We have assumed $Z_\chi \rightarrow t\bar{t}$ and only one flavour of NN allowed in the decay, with $M_N = 20.5 \text{ GeV}/c^2$.

Mode	$M_{Z_\chi} \text{ (GeV}/c^2\text{)}$		
	50	60	70
$\nu_e \bar{\nu}_e = \nu_\mu \bar{\nu}_\mu = \nu_\tau \bar{\nu}_\tau$	5.3	5.1	5.1
$N\bar{N}$	7.0	9.2	10.4
$e^+e^- = \mu^+\mu^- = \tau^+\tau^-$	5.9	5.7	5.6
$u\bar{u} = c\bar{c}$	3.5	3.4	3.4
$d\bar{d} = s\bar{s} = b\bar{b}$	17.6	17.1	16.9
$\Gamma_{\text{tot}} \text{ (MeV)}$	$47 \left[\frac{y}{0.1} \right]$	$83 \left[\frac{y}{0.1} \right]$	$133 \left[\frac{y}{0.1} \right]$
$\Gamma_{\text{tot}} \text{ (Min) (MeV)}$ based on eq. (5.34)	20	68	141

Table 4

Predicted cross-sections times e^+e^- branching ratios for Z^0 ($93.8 \text{ GeV}/c^2$) and Z_χ production (minimum values) in $p\bar{p}$ collisions, in pb. Z_χ cross-sections scale linearly with y , and $y \leq 0.112$.

	$M_{Z_\chi} \text{ (GeV}/c^2\text{)}$	y_{min}	$\sqrt{s} \text{ (GeV)}$			
			540	620	2000	
Z^0	-	-	31	40	156	
Z_χ	50	0.042	3.8	4.5	14	
	55	0.065	5.0	6.0	20	
	60	0.082	5.6	6.7	23	
	65	0.095	5.7	6.9	25	
	70	0.106	5.0	6.2	24	

Figure captions

Fig. 1 : Contours of constant mass eigenvalues for two-Z mixing in a model with $V_2 = 0$. Solid lines correspond to lower eigenvalue and dashed to higher. Labels on lines indicate masses in GeV/c^2 . Shaded regions correspond to no gauge boson within $3 \text{ GeV}/c^2$ of $M_0 \equiv 93.8 \text{ GeV}/c^2$.

(b) is an expanded version of (a). The horizontal line in (a) corresponds to the lower bound on $\hat{g}^2$ in an $\text{SO}(10)$ GUT, where $\text{SO}(10) \rightarrow \text{SU}(5) \times \text{U}(1)$ at the Planck scale [18].

Fig. 2 : Point of minimum χ^2 in $x \equiv \sin^2 \theta_w$ and $y = [g_X^2/(g_L^2 + g'^2)] [M_{Z_0}^2/M_{Z_\chi}^2]$ (cross). Dashed line denotes contour $\chi^2 = \chi_{\min}^2 + 1$.

Fig. 3 : h_{VV}^μ and ΔR as a function of M_{Z_χ} [according to eqs. (5.26) and (5.30)] for $x = 1/4$, $\sqrt{s} = 44 \text{ GeV}$. Heavy lines correspond to values excluded by eq. (5.34).

Fig. 4 : Allowed regions of y and M_{Z_χ} in the unmixed- Z_χ model. Shaded areas are excluded. Solid horizontal line: bound (5.22) from low- q^2 neutral-current phenomenology. Solid curve: bound (5.34) from requiring a minimum contribution of cross-section (5.32). Dashed curve: contour of $h_{VV}^\mu = 0.06$ at $\sqrt{s} = 34 \text{ GeV}$. (We estimate that a larger value is excluded). Dotted curve: contour of $h_{VV}^\mu \approx 0.08$ at $\sqrt{s} = 44 \text{ GeV}$.

Fig. 1

Fig. 2

Fig. 3

Fig. 4