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EVENTS WITH JET + (MISSING ENERGY) AS PAIRS OF NEW NEUTRAL LEPTONS

M. Gronau*)

Stanford Linear Accelerator Center
Stanford, CA 94305

and

J.L. Rosner

CERN - Geneva
and
Enrico Fermi Institute and Department of Physics
University of Chicago, Chicago, IL 60637

ABSTRACT

The process $\bar{p}p \to N_1 N_2 + \ldots$, where N_1 and N_2 are neutral leptons, $N_1 \to$ (neutrals), $N_2 \to$ (jet), is examined as a possible source of events at $\sqrt{s} = 540$ GeV in which single jets are observed opposite missing energy. Some of these events have been interpreted as decays $Z^\circ \to N\bar{N}$, where N is a weak isodoublet. We analyze aspects of this suggestion. The highest-transverse-momentum event would require another source. One possibility is a new neutral gauge boson of mass $\geqslant 115$ GeV/c^2, decaying to pairs of massive right-handed neutrinos.

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*) On leave from The Technion, Haifa, Israel.

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Unusual events observed in $\bar{p}p$ collisions at $\sqrt{s} = 540$ GeV include several of the form[1)]

$$\bar{p}p \to \text{jet} + (\text{missing transverse energy}). \qquad (1)$$

Recently it has been suggested[2)] that some of these events come from production of pairs of neutral massive leptons,

$$\bar{p}p \to \underbrace{N_1}_{\to\ \text{all neutrals}} + \underbrace{N_2}_{\to\ \text{jet}} + \dots \qquad (2)$$

If N_1 ($\equiv \bar{N}_2$) is a heavy weak isodoublet neutrino, three or four of these events can have come from Z° decay. Here we analyze some aspects of this suggestion. We also point out that while one other event (that of highest jet and missing energy) is unlikely to come from Z°, it might have originated in the decay of a heavier gauge boson (> 115 GeV/c^2) to pairs of massive "right-handed" neutrinos. We shall give the arguments for these interpretations, and suggest further experimental signatures.

We summarize in Table I some properties of the six single-jet events mentioned in Ref. 1). The transverse mass of five of them is consistent with a Z° origin. The sixth (A) is about $2\frac{1}{2}\sigma$ above a Z° mass.

If a weak isodoublet massive neutrino ν_H exists, the branching ratio $B(Z^\circ \to \nu_H\bar{\nu}_H)$ is expected to be about 6%[*)]. The ν_H will decay, in turn, via mixing with lighter neutrinos. For the mechanism we discuss, this mixing must permit neutral-current as well as charged-current decays. An example of this mixing would be

$$\nu_H \approx \nu_H^\circ + \sum_{i=e,\mu,\tau} U_{Hi}\,\nu_i \quad , \qquad (3)$$

in which ν_H° belongs to a doublet of weak SU(2) interacting right-handedly with charged W's [in a multiplet (E^-, ν_H°), $m_{E^-} > m_{\nu_H^\circ}$) and with the standard Z°. This type of state is sometimes known as a "mirror fermion"[3)-5)]. The GIM mechanism for left-handed currents then is frustrated, and ν_H° will be able to decay both via charged and via neutral left-handed currents. From the standpoint of such currents, ν_H° may be considered "inert".

[*)] This assumes that there are no other members of the ν_H generation lighter than $m_Z/2$. If such members exist, $B(Z^\circ \to \nu_H\bar{\nu}_H)$ is slightly smaller.

The phenomenology of a heavy neutral lepton mixing with the light neutrinos and an "inert" state ν_H° has been discussed in some detail in Ref. 6). For ν_H in the mass range of 2 to 20 GeV/c^2 the typical decays of such a neutrino mixing primarily with ν_e or ν_μ are

$$B(\nu_H \to \ell^+ \ell'^- \nu) \simeq 0.2 \qquad (4)$$

$$B(\nu_H \to \nu\nu\bar{\nu}) \simeq 0.1 \qquad (5)$$

$$B(\nu_H \to \ell^- + \text{hadrons}) \simeq 0.5 \qquad (6)$$

$$B(\nu_H \to \nu + \text{hadrons}) \simeq 0.2 . \qquad (7)$$

If ν_H mixes primarily with ν_τ and is quite light, the neutral-current modes (5) and (7) can be considerably more important.

The combined branching ratio for Z° decays in the process (2) is then expected to be

$$B(Z^\circ \to \text{jet} + [\text{all neutrals}])$$

$$= (6\%)(2)(0.1)(0.5 + 0.2 + 0.2) \simeq 1\% . \qquad (8)$$

This is to be compared with $B(Z^\circ \to e^+e^-) \simeq 3\%$ expected in the standard SU(2)×U(1) picture.

The observed cross-sections for $\bar{p}p \to Z^\circ \to e^+e^-$ are 71±24±13 pb[7)] on the basis of four events[8)] and 110±40±20 pb on the basis of eight events[9)]. Let us imagine that the true e^+e^- cross-section lies somewhat above 70 pb. Then for an exposure of $\int L dt \geqslant 100$ nb^{-1} obtained in each experiment, one would expect at least two events of the form (2) in each experiment if detection efficiencies were similar to those for e^+e^-. It is quite conceivable that all would have been observed in one experiment[1)] and not in the other[10)]. [In Ref. 2), a wider range of possibilities is considered for $B(\nu_H \to$ all neutrals).]

A key test of the heavy-lepton idea[2)] is the presence of at least one charged lepton in the majority of the jets due to the lepton ν_H, as one sees from Eqs. (4) and (6). Event "A" indeed has an energetic muon. The invariant mass of the muon and the rest of the jet is quoted as about 5 GeV/c^2. Event "B" has only three charged tracks of effective mass 0.8 GeV/c^2. Event "D" could contain one or two electrons. The jet effective mass is 3.1 GeV/c^2.

The observed charged particle multiplicities of the jets in the single jet events is low, n_c = 1-4. This multiplicity is much lower than that of typical quark and gluon jets at such high energies, $E_{jet} > 40$ GeV. The decay of a neutral lepton with a mass of a couple of GeV is expected to lead to such low multiplicities. For instance, for $M_{\nu_H} = m_\tau$ we estimate $\langle n_c \rangle = 1.8$ using Eqs. (4)-(7) and the measured τ decay multiplicities.

Production of a pair of neutral massive leptons is one possible explanation of a recent event observed in e^+e^- interactions 11). However, the most likely mass for these leptons is around 20 GeV/c^2, which appears rather high in comparison with the values quoted above.

The event "A" appears unlikely to be due to Z decay, since the total transverse mass is somewhat too high. We have examined the possibility that it is due to the decay of a new gauge boson Z_χ with a large coupling to pairs of right-handed neutrinos. This boson arises when one gauges I_{3R} and B-L separately, rather than just in the combination $Y = 2I_{3R} + B-L$ 12),13). Normally one writes $Q = I_{3L} + Y/2$ and gauges just I_{3L} and Y, obtaining the physical photon and Z° as mixtures of bosons coupling to these two charges. A more symmetric form is $Q = I_{3L} + I_{3R} + (B-L)/2$. If one gauges I_{3L}, I_{3R}, and B-L separately, a right-handed neutrino N corresponding to each left-handed neutrino ν suffices to banish anomalies in all currents, and there is a unique combination of I_{3L}, I_{3R}, and B-L orthogonal to that in γ and Z°, to which a new boson Z_χ couples. In the absence of mixing between Z_χ and γ or Z°, this charge is 13)-15)

$$Q_\chi = \frac{1}{\sqrt{10}} \left[5 I_{3R} + 3 (I_{3L} - Q) \right] . \qquad (9)$$

The charge Q_χ is normalized so that $\Sigma Q_\chi^2 = \Sigma I_{3L}^2 = \Sigma I_{3R}^2 = 2$ for a generation of quarks and leptons (with the right-handed neutrino included). The values of Q_χ for members of a generation are shown in Table II. The right-handed neutrino N has the largest Q_χ charge of any generation member.

The phenomenology of "extra-Z" bosons such as Z_χ has been studied in detail elsewhere 12)-22). Typically the mass of such bosons has to be taken above 200 GeV/c^2 in order not to disturb low-energy neutral current interactions too much. However, this conclusion depends on the Higgs bosons chosen to break SU(2)×U(1)×U(1) to $U(1)_{e.m.}$ and on the over-all strength of the $U(1)_\chi$ coupling, which is taken from grand unification. If this coupling is taken weaker, the Z_χ mass can be lower. An extreme example has been studied in Ref. 22), where even a Z_χ between 50 and 70 GeV/c^2 is shown to be possible [as a source of the event of Ref. 11)].

As one example, we have considered a model 22) in which Higgs mesons are chosen so that the Z° and Z_χ do not mix with one another. Such a choice is indeed possible, and ensures that the Z° mass will not be pushed by mixing from its predicted value in the standard picture. We choose g_χ small enough not to disturb low q^2 neutral current phenomenology. We then find $\sigma(\bar{p}p \to Z_\chi \to N\bar{N}) \leq O(1\text{-}6 \text{ pb})$ for M_{Z_χ} = 130-170 GeV/c^2, $\sqrt{s}$ = 540 GeV *). Allowing for one N to decay to neutrals and the other to decay to a jet, one finds it hard to obtain a cross-section much above 1 pb for the combined process (2). This would correspond to about a 10% probability for observing the event "A" in the experiment of Ref. 1).

Another possibility for a relatively light Z_χ has been raised by the analysis of Ref. 16). There exists a choice of Higgs bosons 14),15) for which the major constraint on M_{Z_χ} comes from parity violation in atomic physics. It is then possible to satisfy all low-energy neutral-current constraints, within the context of a grand unified theory, with a mass of Z_χ as low as 170 GeV/c^2. However, this would entail a 5% downward shift of the observed Z mass from its predicted value in the standard picture, $M_{Z°} \equiv 93.8^{+2.4}_{-2.2}$ GeV/c^2 24). It would also entail a forward-backward asymmetry in $e^+e^- \to \mu^+\mu^-$ about 20-25% larger than in the standard model.

If N is a Majorana neutrino, it can decay to either sign of muon. There are dimuon + jet(s) events with high total effective mass (but $m_{\mu\mu} \leq 22$ GeV/c^2) seen in $\bar{p}p$ collisions at $\sqrt{s}$ = 540 GeV 7),25), one involving $\mu^+\mu^-$ and another involving $\mu^-\mu^-$. If these are not due to some more "conventional" source (such as $W \to t\bar{b}$), they could also be due to the process just suggested for event "A".

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*) The cross-section calculations are described in more detail in Ref. 22. We use structure functions of Ref. 23), whose authors we thank for providing them in numerical form prior to publication. These lead to the lower cross-section estimates. The higher estimates come from assuming $u_v(x) = 2.19x^{-\frac{1}{2}} (1-x)^3$ (valence u); $d_v(x) = 1.23x^{-\frac{1}{2}} (1-x)^4$ (valence d); $\xi(x) = 0.24x^{-1} (1-x)^7$ (sea).

There are eight other $\mu\mu$ events with $6 \leq m_{\mu\mu} \leq 22$ GeV/c^2 seen by UA1. If any of these is to have come from $Z° \to \bar{N}N$ decay, some energy has to have been carried off by neutrinos in the decay of N. Examples of such decays could involve $N \to \mu\mu\nu$, $\bar{N} \to \nu$ + jet(s). However, it is quite possible that some or all of these eight events could be due to semileptonic b decays²⁶⁾.

The event "A" of Ref. 1) in fact bears some resemblance to an event consisting of W($\to e\nu$) + jet seen in the UA2 detector [event "B" of Ref. 27)]. In a separate note²⁸⁾ we have discussed the possibility that one of the UA2 events ("C", consisting of W + 2 jets) involves production of a pair of heavy quarks, each of which decays to a real W. Such an explanation does not seem plausible for events "B" of Ref. 27) or "A" of Ref. 1). The attempt to explain event "B" of Ref. 27) in terms of a pair of neutral leptons would require a large neutral lepton mass, since M(e + jet) in that event is about 32 GeV/c^2. One would then fail to explain most of the monojet events of Table I in terms of a similar mechanism, unless more than one such lepton were being seen. [In fact, proposals do exist for just such a "zoo" of leptons in the 2-35 GeV mass range⁵⁾].

Events also have been observed in which a single photon recoils against missing transverse momentum¹⁾. One of these events ("G") may well be $W \to e\nu$ in which the electron track has been missed. The other ("H") could in principle be due to a decay of the form (7), in which all hadrons are neutral. This would only be plausible for very small ν_H masses. In Ref. 2), such events have been ascribed to radiative decays of ν_H, which can be important with proper choices of mass and mixing parameters. The present discussion, in contrast to that of Ref. 2) seems to have no natural place for $Z° \to e^+e^-\gamma$ or $Z° \to \mu^+\mu^-\gamma$ events, which have also been reported^{8),9)}.

What are further tests of the present mechanism?

1) The cross-section for production of any weak isodoublet neutrino via the Z° pole in e^+e^- annihilations is¹¹⁾:

$$\sigma(e^+e^- \to \nu_H \bar{\nu}_H) = \frac{(G_F M_Z^2)^2}{96\pi} \frac{s}{(M_Z^2 - s)^2} \beta (3 + \beta^2)(1 - 4x + 8x^2), \qquad (10)$$

where $\beta \equiv (1 - 4m^2_{\nu_H}/s)^{\frac{1}{2}}$ is the velocity of ν_H in the e^+e^- centre-of-mass system, and $x = \sin^2\theta_W$. For small m_{ν_H}, $x = 0.22$, and $s \ll M_Z^2$, we find $\sigma = 0.3$ pb $(\sqrt{s}/30 \text{ GeV})^2$. The final states (4)-(7) make for a variety of detection possibilities: monojets, unusual leptons, unexpected combinations of leptons and hadrons, etc. The neutral-current decays in particular would distinguish leptons which might be responsible for the single-jet events of Ref. 1) from more conventional fourth-generation neutrinos without such neutral-current decays²⁹⁾.

2) The decays $Z° \to$ (2 jets) are expected to be the major signature of $Z° \to \nu_H\bar{\nu}_H$. These jets may be distinct from those of $Z° \to q\bar{q}$ or from QCD background as a result of their large expected lepton content. Events with $Z° \to \mu\mu + \ldots$, $Z° \to 3\mu + \ldots$, or with both muons and electrons in the final state of Z° decays, are all possible.

3) The mixing amplitudes in Eq. (3) are unknown, but unlikely to exceed 0.1 in magnitude⁶⁾. The possiblity of extremely weak mixing may permit ν_H lifetimes to be long enough to be detected. Elsewhere⁶⁾ we have estimated:

$$\tau_{\nu_H} = (4\text{-}5) \times 10^{-12}\,\text{s} \left(\frac{M_{\nu_H}}{1\ \text{GeV}/c^2}\right)^{-5.2} |U|^{-2} \qquad (11)$$

for ν_H mixing mainly with ν_e or ν_μ, and $M_{\nu_H} \leq 50$ GeV/c^2. It may pay to examine the point of origin of the single-jet events, or the coincidence of the points of origin of two jets in $Z° \to$ (2 jet) candidates, to see if a finite lifetime can be detected. Even longer ν_H lifetimes than those predicted by Eq. (11) have been suggested in more general models²⁾.

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Table I - Properties of single-jet events in $\bar{p}p$ collisions at $\sqrt{s}$ = 540 GeV[1)]

Event	E_T(jet) (GeV)	ΔE_M [a)] (GeV)	$m_T(\text{jet},\Delta E_M)$ (GeV/c^2)
A	71 [b)]	66±8 [b)]	130±16 [b)]
B	48	59±7	106±12
C	52	46±8	97±17
D	43	42±6	85±12
E	46	41±7	87±14
F [c)]	39	34±7	73±14

a) missing transverse energy;
b) high-momentum muon included in jet: $p_T^\mu = 46^{+12}_{-8}$ GeV/c.
c) this event is consistent with $W \rightarrow \tau\nu$.

Table II - Relative amplitudes for coupling of a gauge boson Z_χ to left-handed fermions. (Reverse signs for right-handed antifermions).

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

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