Characteristics of Dimuons as Evidence for a New Quantum Number*

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Neutrino-induced dimuon events probably involve the production and subsequent decay of one or more real, intermediate particles. The observed properties of dimuon events are shown not to agree with the hypotheses that the intermediate particles are heavy leptons or semiweak vector bosons. This strongly suggests production of new hadrons as the leading explanation of dimuon events. Such new hadrons, decaying weakly, would necessarily possess a new, as yet unidentified, quantum number.

The observation of neutrino-induced events in which two muons are observed in the final state has been reported in two earlier papers.[1] Lepton conservation requires that an unobserved third lepton be present in the final state of such (dimuon) events. Hence, in general, the empirical description of the reaction giving rise to dimuon events is either

$$\nu_\mu + (A,Z) \to \nu_\mu + \mu^- + \mu^+ + \text{hadrons} \quad (1)$$

or

$$\nu_\mu + (A,Z) \to \mu^- + \mu^+ + \mu^- + \text{hadrons} \quad (2)$$

or some combination of (1) and (2). Reaction (2) is not likely to be the primary source of the observed dimuon events because no events with three final state muons (trimuons) have been detected, even though the experimental detection efficiency for trimuons is comparable with that for dimuons. Reaction (1) is expected to occur directly through the exchange of a photon emitted by the μ^+ or μ^- and absorbed by (A,Z), but the calculated cross section is about three orders of magnitude less than the observed rate of dimuon production.[2] It is probable, therefore, that neutrino-induced dimuon events proceed through Reaction (1), but with the production and subsequent decay of one or more real, intermediate particles with lifetimes appreciably less and masses appreciably greater than those of charged pions and kaons.[1] It is the purpose of this paper to analyze the characteristics of the observed dimuon events to specify further those intermediate particles.

Feynman diagrams corresponding to possible sources of Reaction (1) are shown in Fig. 1, where (a) describes charged, intermediate-vector-boson ($W^\pm$) production and decay, (b) describes neutral, heavy-lepton (L^0) production and decay, and (c) shows hadron production and decay at the lower vertex. We have omitted from Fig. 1 the diagrams for neutral, intermediate-vector-boson (W^0) production and charged, heavy-lepton ($L^\pm$) production because the decay $W^0 \to \mu^+ + \mu^-$

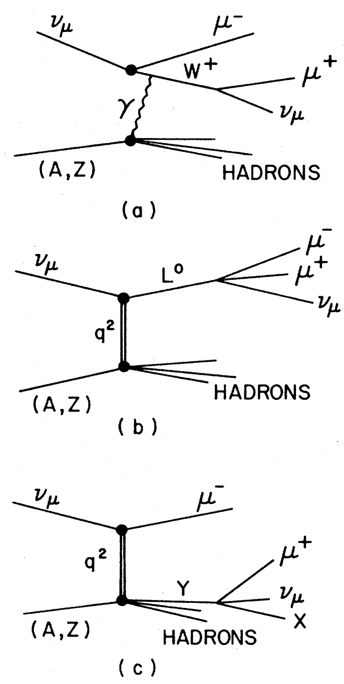

FIG. 1. Feynman diagrams for neutrino-induced production and subsequent decay of (a) charged intermediate vector boson, W^+, (b) neutral heavy lepton, L^0, and (c) new hadron, Y. For brevity, the second diagram belonging to (a) in which the photon is emitted by the μ^- is not shown.

would give rise to sharp structure in the dimuon invariant mass distribution which is not observed,[1] and the decays $L^{\pm}\rightarrow \mu^{\pm}+\nu_{\mu}(\bar{\nu}_{\mu})+\nu_{\mu}(\bar{\nu}_{\mu})$ and $L^{\pm}\rightarrow \mu^{\pm}$ +hadrons lead only to single-muon final states.

Within certain limitations, the consequences of the hypotheses of new-lepton and intermediate-vector-boson production and decay may be directly calculated[3,4] and compared with experiment to find evidence either in favor of or against new-particle production at the lepton vertex of the diagrams in Figs. 1(a) and 1(b).

Figure 2(a) presents the observed, corrected distribution in dimuon invariant mass, $M_{\mu\mu}=2(p_+ \times p_- \sin^2\theta_{\mu\mu}/2)^{1/2}$, where $\theta_{\mu\mu}$ is the angle between the two muons. Shown also in Fig. 2(a) are the distributions in $M_{\mu\mu}$ predicted[3] for the decay $L^0 \rightarrow \mu^+ + \mu^- + \nu_\mu$ with $M_L = 4$, 6, and 8 GeV/c^2. No distribution calculated for a single mass is a good fit to the data, nor are lower- or higher-mass heavy leptons suggested. Note also that there is no significant indication of sharp structure in the observed distribution such as would arise from a W^0.

We show in Fig. 2(b) the scatter plot of the momenta p_- and p_+ of the negative and positive muons, respectively, in each of the dimuon events. There are nine events with $p_+ > p_-$ that might be the products of interactions induced by incident antineutrinos. Including all events in Fig. 2(b), one finds $\langle p_-\rangle/\langle p_+\rangle = 3.7 \pm 0.65$, where the error is determined solely from the uncertainties in the momentum measurements and the number of events; eliminating the nine events with $p_+ > p_-$ yields $\langle p_-\rangle/\langle p_+\rangle = 6.1 \pm 0.8$. It is important to note that L^0 production and decay predicts the limits $0.48 \leq \langle p_-\rangle/\langle p_+\rangle \leq 2.1$ for any mixed neutrino and antineutrino beam, independent of any assumptions underlying the heavy-lepton calculations,[5] *including production of* L^0 *through* $L^{\pm}$ *decay.* This is in contrast to the subsequent comparisons giv-

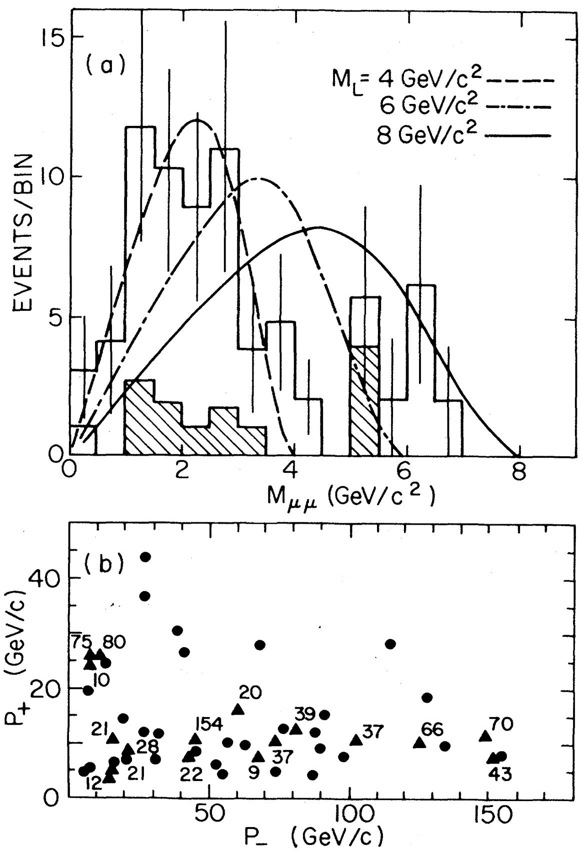

FIG. 2. (a) Observed distribution in invariant dimuon mass, $M_{\mu\mu}$, and predictions for $M_L = 4$, 6, and 8 GeV/c^2. The cross-hatched events have $p_+ > p_-$. (b) Scatter plot of momenta of the negative and positive muons of each dimuon event. Triangles denote calorimeter events, with the adjacent numbers giving the associated values of E_H; circles denote counter events. Three of the observed 51 events are off scale with values of p_+ and p_-, respectively, of 20 and 205, 90 and 18, 67 and 30, all in GeV/c.

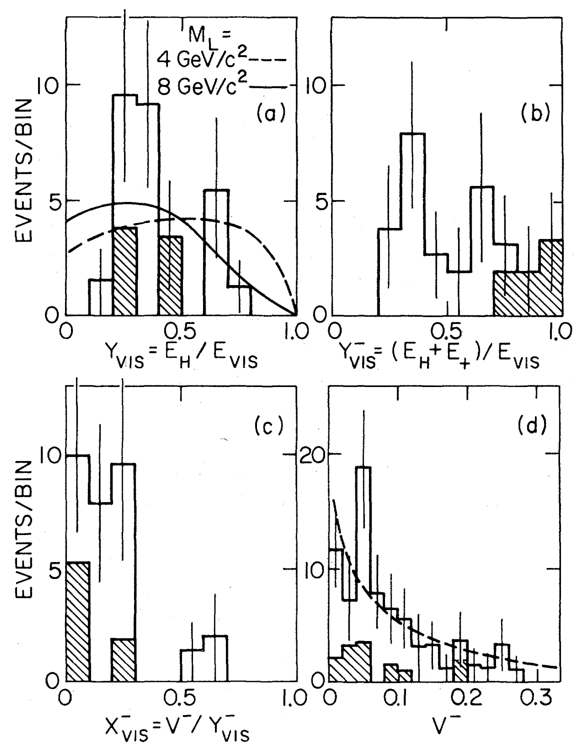

FIG. 3. Distributions in (a) y_{vis}, (b) y_{vis}^-, (c) x_{vis}^-, and (d) v^-. The curve in (d) is the observed distribution for single-muon events.

en here which depend on the details of the heavy-lepton model.

In Fig. 3(a) is presented the observed, corrected distribution in $y_{\rm vis} = E_H/E_{\rm vis}$, where E_H is the measured total energy of the hadron cascade in the dimuon events occurring in the ionization calorimeter,[1] and $E_{\rm vis} = E_H + E_- + E_+$. We show in Fig. 3(b) the distribution in the variable $y_{\rm vis}^- = (E_{\rm vis} - E_-)/E_{\rm vis}$, which is appropriate to $W^\pm$ production [Fig. 1(a)] and hadron production [Fig. 1(c)]. In Fig. 3(c) is given the distribution in the variable $x_{\rm vis}^- = v^-/y_{\rm vis}^-$, where $v^- = 2(E_-/m)\sin^2(\theta_-/2)$, and m is the nucleon mass. The distribution in v^- is presented in Fig. 3(d), and is in approximate agreement with that observed for deep-inelastic single-muon events.

Finally, in Fig. 4(a) is shown the distribution in $E_{\rm vis}$ compared with the predictions for heavy leptons of different mass. In Fig. 4(b) we present the corresponding comparison for the distribution in $W_{\rm min}$, the minimum total mass recoiling against the negative muon.[1]

The dimuon data shown are not consistent with

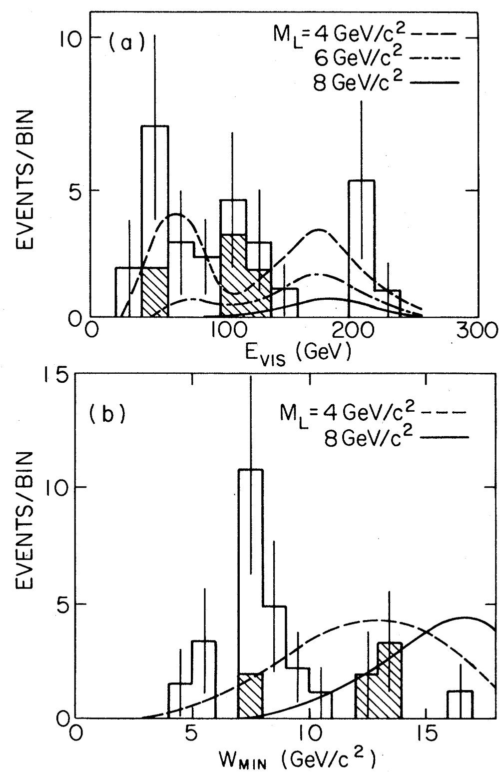

FIG. 4. Distributions in (a) $E_{\rm vis}$ and (b) $W_{\rm min}$ compared with heavy-lepton predictions. The data and calculated curves in (a) are normalized absolutely, assuming $(G_0/G_c)^2 = 0.2$ and $\Gamma(L^0 \to \mu^+ + \mu^- + \nu_\mu)/\Gamma(L^0 \to \text{all}) = 0.1$.

low mass ($\lesssim 10$ GeV/c^2) $W^\pm$ production and decay into $\mu^\pm + \nu_\mu(\bar\nu_\mu)$ for the following reasons. (i) The ratio of the average momenta $\langle p_-\rangle/\langle p_+\rangle$ is observed to be significantly greater than unity but is predicted to be significantly less than unity (~ 0.4) for $W^\pm$ production and decay.[4] (ii) This same momentum asymmetry would lead to a $y_{\rm vis}^-$ distribution dominated by events with $y_{\rm vis}^- > 0.5$, contrary to the observed distribution in Fig. 3(b). (iii) The dependence of $\langle Q^2\rangle = 2mE_\nu\langle v\rangle$ on E_ν of the deep-inelastic single-muon events would show an appreciable departure from linearity due to the effect of a propagator of mass less than about 10 GeV/c^2, which is not observed.[6] (iv) The production of $W^\pm$ is expected to occur more frequently as a quasicoherent process than as an inelastic process,[4] which is not in agreement with the preponderance of observed dimuon events with large E_H [Fig. 3(b)].

Similarly, the dimuon data are not consistent with L^0 production and decay into $\mu^+ + \mu^- + \nu_\mu$, with $M_L \lesssim 10$ GeV/c^2, for the following reasons: (i) the difficulty of fitting the observed $M_{\mu\mu}$ distribution with the decay products of a single L^0 as shown in Fig. 2(a); (ii) the difference in the calculated limit and the measured ratio $\langle p_-\rangle/\langle p_+\rangle$ obtained from Fig. 2(b); (iii) the questionable agreement of the calculated and observed distributions for $y_{\rm vis}$ in Fig. 3(a); (iv) the poor agreement of the observed and calculated distributions for $W_{\rm min}$ in Fig. 4(b).

Furthermore, the observation of dimuon events with both muons having the same sign[1] (−/−) is evidence against both $W^\pm$ and L^0 as possible explanations of dimuons and, indeed, against any explanation that attributes the origin of dimuons to the lepton vertex of the interaction as in Figs. 1(a) and 1(b). Dimuons of the same sign are, however, consistent with new-particle production at the hadron vertex as in Fig. 1(c).

Failure to account for the observed dimuon characteristics by either a heavy lepton or intermediate vector boson strongly suggests new-hadron (Y) production [Fig. 1(c)] as the leading explanation of dimuons. Such a new hadron or hadrons, decaying weakly to a muon, a neutrino, and possibly other hadrons, would necessarily possess a new, as yet unidentified, quantum number, not conserved by the weak interaction. It is the conservation of this quantum number that prevents decay of the new hadron by strong or electromagnetic processes, neither of which give rise to the second muon and the missing neutrino in Reaction (1). The observed ratio of (−/−) to (+/

−) dimuon events (~0.1) indicates the operation of an approximate selection rule in the decay of the Y particle, relating the change in the new quantum number to the change in charge of the hadrons involved in the decay. The distribution in p_t (Fig. 3 of Ref. 1) and the distribution in $W_{\rm min}$ [Fig. 4(b) here] confirm our earlier estimate that the mass of at least one Y particle lies between 2 and 4 GeV/c^2.

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Neutral Heavy Leptons as a Source for Dimuon Events: A Criterion*

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Suppose that a neutral, heavy, spin-$\frac{1}{2}$ lepton were created by a mixed neutrino-antineutrino beam incident on an arbitrary target and that this lepton subsequently decayed into a μ pair and a neutrino (or antineutrino). Then the ratio of the respective mean laboratory energies for the μ^- and μ^+ lies between 0.48 and 2.10.

In an accompanying Letter,[1] Benvenuti *et al.* analyze their dimuon data in an attempt to narrow the range of mechanisms that might account for the phenomenon in which a pair of prompt muons appears in the final state of neutrino-induced reactions. For the bulk of the observed events, the two muons are oppositely charged; and for these, one of the possible sources that has to be considered is production of a heavy neutral lepton L^0, followed by the decay $L^0 \to \mu^- + \mu^+ + \nu$. The expected characteristics of the muon spectra on such a picture have been worked out by several authors.[2] In comparing their data with these theoretical predictions, Benvenuti *et al.* come to the conclusion that the heavy-lepton interpretation cannot easily be sustained. This strengthens the case for an alternative interpretation in which one of the muons is produced directly in the neutrino reaction, the other muon arising from decay of a new kind of hadron produced in the neutrino reaction.

One of the decisive considerations that enters into the case against a heavy-lepton source for the dimuons is the observation of a striking difference in the energy spectra of μ^- and μ^+. The observed ratio[3] of the mean laboratory energies is $R \equiv \langle E(\mu^-)\rangle/\langle E(\mu^+)\rangle = 3.7 \pm 0.65$. In contrast, the theoretical analyses have yielded considerably smaller values, in the vicinity of $R = 1.5$ and only mildly dependent on the heavy-lepton mass. Differences between the μ^- and μ^+ spectra can arise on the heavy-lepton picture if the interactions responsible for the decay contain both even and odd terms with respect to charge conjugation—on a current-current picture, if the charged lepton current contains both vector and axial-vector pieces. The precise spectral expectations are determined in part by the relative strengths of these two couplings, and these depend, for example, on the neutral- versus charged-current contributions to the effective interactions. However, the spectral features will also depend on the polarization and velocity distributions of the heavy leptons. In these several ways,