Characteristics of Neutrino-Produced Dimuon and Trimuon Events as Evidence for New Physics at the Lepton Vertex*

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The characteristics of six trimuon events observed in the new large-angle neutrino detector at Fermilab are described. The leptonic system appears to take an inordinate fraction of the incident neutrino energy if new hadrons are presumed to be the origin of these events. A similar effect seems to be present in the dimuon events previously observed. The events find a natural interpretation as the products of cascade decay of a new lepton (the M particle) through a lower-mass neutral lepton (the L^0 particle).

In a previous Letter, we have reported the existence and general properties of six trimuon events produced in the new large-angle neutrino detector (NEULAND) at Fermilab.[1] We have previously reported the production of dimuon events by high-energy neutrinos and antineutrinos.[2-4] While the bulk of these dimuon events almost certainly come from new hadrons, a significant fraction may also arise from new lepton production. In Fig. 1 we show a scatter plot of the μ^+ and μ^- momenta for all events collected previously.[5]

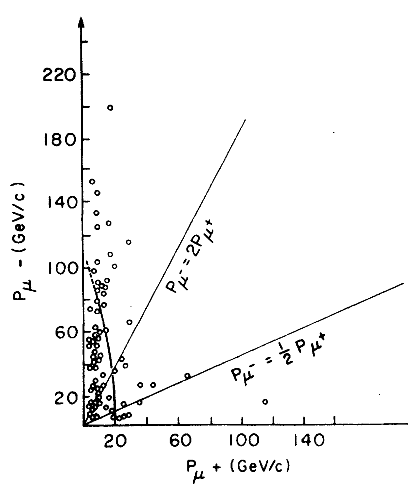

FIG. 1. Positive- and negative-muon momentum scatter plot for dimuon recorded in the previous Harvard-Pennsylvania-Wisconsin-Fermilab experiments that used a quadrupole-triplet or bare-target neutrino beam. The solid line indicates the results of a Monte Carlo calculation for charmed-particle production by Barger and Gottschalk (Ref. 6). No events were generated outside the solid line from a sample of 1000 dimuons.

There is a clear band of events with large P_{μ^-} and much smaller P_{μ^+}. These events have been attributed to charmed-particle production and subsequent semileptonic decay.[2] Note, however, that there are ten events within the band $P_{\mu^-} = 2P_{\mu^+}$ and $P_{\mu^-} = \frac{1}{2}P_{\mu^+}$ which also have combined P_{μ^+} and P_{μ^-} momenta of greater than 40 GeV. These events are candidates for heavy-lepton production and decay through the process

$$\nu_\mu + N \to L^0 + X, \quad L^0 \to \mu^+ + \mu^- + \nu.$$

Furthermore, the results of a detailed Monte Carlo simulation of charmed-particle production is shown in Fig. 1, indicating that events which have P_{μ^-} and P_{μ^+} values outside this boundary are unlikely to arise from charm production.[6]

Further information concerning the origin of dimuon events can be obtained by considering the correlation between $\Delta\varphi$, the difference in azimuthal angles of the transverse momenta of the muons, and the momentum of the lowest-energy muon, presumed to originate from the decay of a charmed particle produced at the hadron vertex.[7,8] It is expected that, for events in which the secondary μ carries a large fraction of the energy of the hadron system, the decay muon and the primary muon will emerge with $\Delta\varphi \sim 180°$. This correlation is borne out by a detailed Monte Carlo calculation by Barger and Gottschalk which is displayed in Fig. 2(a).[6] In Fig. 2(b) a scatter plot of $\Delta\varphi$ vs P_μ for dimuon events is given for the quadrupole-triplet neutrino spectrum. Note that there are ten $\mu^+\mu^-$ and three $\mu^-\mu^-$ events that fall outside the contour for charmed-particle production.

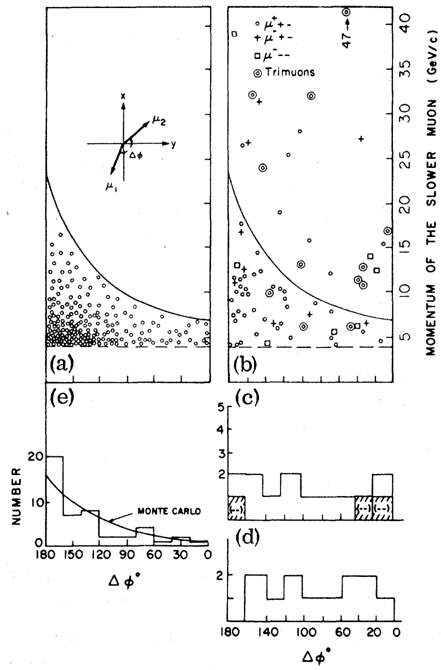

FIG. 2. (a) $\Delta\varphi$ vs P_{μ^+} scatter plot from Monte Carlo produced charmed-particle events. $\Delta\varphi$ is defined in the inset. (b) Scatter plot of $\Delta\varphi$ vs P_{μ_s} for the observed dimuon and trimuon events (only dimuon events from the quadrupole-triplet run are used here). Here P_{μ_s} is the lowest-momentum muon for each dimuon event or for each dimuon from a trimuon event. Also shown is the expected boundary for charm production from (a). (c) $\Delta\varphi$ distribution for dimuon events above the charm contour. (d) $\Delta\varphi$ distribution for all trimuon events. In one event (event 135), the errors in p_x and p_y of the μ^+ are large enough to affect the value of $\Delta\varphi$ substantially. All other events have uncertainties in $\Delta\varphi$ of roughly 1 bin width. (e) $\Delta\varphi$ distribution for dimuon events below the charm contour compared with the Monte Carlo results.

Many of these events are the events noted as "symmetric" in Fig. 1. Henceforth we label the events outside the charm contour as "symmetric" dimuons. The $\Delta\varphi$ distribution for the events with a high-energy secondary muon is consistent with being flat whereas any model where the second muon comes from the hadronic vertex is expected to give a strong peaking near 180°. In Fig. 2(c) the projected $\Delta\varphi$ distribution is shown for the dimuon events that fall outside the charm contour in Fig. 2(c). In Fig. 2(d) the distribution for the trimuon events is shown using the $\Delta\varphi$ between each pair of muons. Figure 2(e) shows events within the charm contour compared with the Monte Carlo calculation. The agreement between the data and the calculation is excellent, while the distributions for the "symmetric" dimuons and trimuons are consistent with being flat. Thus, it is probable that at least ten $\mu^+\mu^-$ and three $\mu^-\mu^-$ events do not arise from the hadronic vertex.

We discuss these data in order to point out that previous experiments have *not* ruled out neutral-heavy-lepton production by neutrinos, but only have established that the majority of the dimuon events arise from hadronic decay.

We now turn to the trimuon events and the distinguishing characteristics.[1] The salient features of the trimuon events are the following: (1) All observed events are of the type $\mu^-\mu^-\mu^+$ and therefore almost certainly arise from a neutrino interaction. (2) Several events have small angles between the three muons. (3) All events have at least two energetic muons. (4) The rate of trimuon production at high energy is estimated to be ~5% of the dimuon rate.[9] (5) For one event (event 119-018991), the energy carried by the three-muon system is much larger than the hadronic energy (13 GeV) and the relative angle between the two high-energy muons is 16 mrad.[1] The total energy of this $\mu^+\mu^-$ system is 204 GeV.

Events with two muons that come from the hadronic vertex are expected to yield low-energy muons. This is confirmed by the existing data on dimuon events shown in Fig. 1 and from the data on μ^-e^+ events obtained in several bubble-chamber experiments.[10] A comparison to the trimuon data can be made by defining $\Sigma \equiv P_{\mu^+} + P_{\mu_2^-}$, where $P_{\mu_2^-}$ is the momentum of the less energetic μ^-. In Fig. 3(a) a plot of $P_{\mu_f^-}$ vs Σ is shown for the trimuon events. These data suggest a ratio

$$\langle P_{\mu_f^-}\rangle / \langle \overline{\Sigma} \rangle \sim 1$$

which would be incompatible with a hadronic origin for which one expects this ratio to be ~5–10.

An interesting empirical correlation in the six trimuon events is shown in Fig. 3(b) where the opening angle is plotted for the $\mu^+\mu^-$ combination with the higher-energy μ^- (fast) and the lower-energy μ^- (slow). Note that for nearly every event the fast μ^- and μ^+ have a smaller opening angle than the other combination. This correlation is improbable even for the small sample of six events. If the "natural" pairing of the μ^- and μ^+ by opening angle is chosen, then the resulting Σ spectrum is given in Fig. 3(a). This spectrum is decidedly uncharacteristic of the expectation for dimuons from the hadronic vertex.

Failing to explain these events through a hadronic origin leads us to suggest that these events

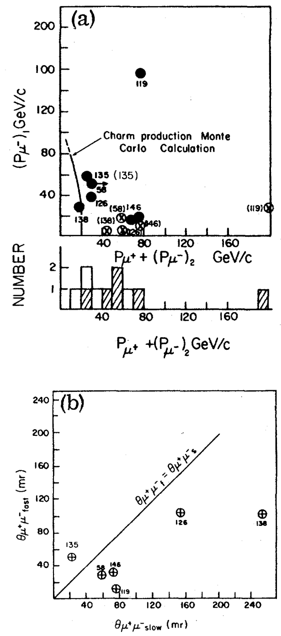

FIG. 3. (a) Scatter plot of $P_{\mu_1^-}$ vs Σ, the sum of the μ^+ and μ_2^- momenta (i.e., $\Sigma = P_{\mu^+} + P_{\mu_2^-}$). $\bullet$, $\mu_1^- = \mu_f^-$ and $\mu_2^- = \mu_s^-$; $\otimes$, μ_2^- is the μ^- with the smallest opening angle with respect to the μ^+ ($\theta_{\mu^+\mu^-}{}^{\min}$). Also shown, for comparison is the results of the Monte Carlo calculation for dimuon production through charmed-particle production and decay. The Σ momentum spectrum is also shown for the two pairings of μ_2^- (cross-hatched for μ_2^- with $\theta_{\mu^+\mu^-}{}^{\min}$). (b) Scatter plot of the opening angle between μ^+ and μ^- for the two combinations of $\mu^+\mu^-$.

may arise from the leptonic vertex. For the $\mu^+\mu^-$ dimuon events it would be sufficient to postulate, for example, the production of massive neutral lepton (L^0) with subsequent decay into two muons.[11] The trimuon and $\mu^-\mu^-$ events seem to require more than one new lepton in order to account for the muons.[12] We cannot determine whether the second lepton is neutral or charged and, for convenience, designate it as the M lepton.[13] We, therefore, postulate the sequence:

$$M \to \mu^- + L^0 + \text{(presumably a neutrino)};$$

$$L^0 \to \mu^+ + \mu^- + \text{(presumably a neutrino)}.$$

In order to estimate the masses of these particles we turn to the dimuon and trimuon invariant-mass distributions. Figure 4(a) shows a scatter plot of the two $\mu^+\mu^-$ mass combinations of the trimuon events, paired by the relative energy of the μ^- (fast or slow). It is remarkable that the $M_{\mu^+\mu^-}$ for the fast μ^- is generally smaller than for the

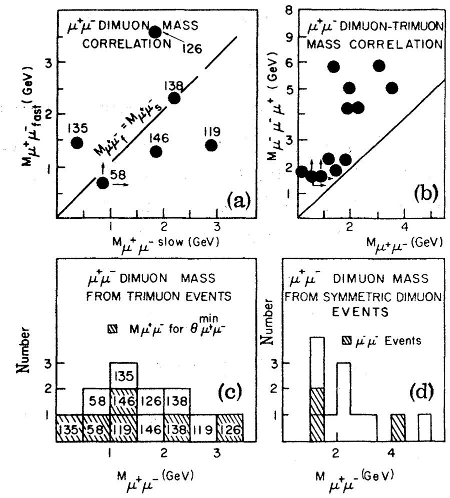

FIG. 4. (a) Scatter plot of the $M_{\mu^+\mu^-}$ for the $\mu^+\mu^-$ combinations. Note that $M_{\mu^+\mu_s^-} = 0.3\,^{+1.5}_{-0.3}$ GeV for event 135. (b) Scatter plot of the $\mu^-\mu^-\mu^+$ mass vs the two combinations of $\mu^+\mu^-$ mass. (c) The $M_{\mu^+\mu^-}$ mass distribution from dimuon events with both combinations. The pairing chosen by the smallest $\theta_{\mu^+\mu^-}$ angle is cross-hatched. (d) The $M_{\mu\mu}$ distribution for events above the charm contour in Fig. 2(b).

other combination; this is a consequence of the smaller opening angle between the $\mu^+\mu_f^-$ discussed previously. Figure 4(b) shows a scatter plot of the $\mu^+\mu^-$ and $\mu^-\mu^-\mu^+$ mass combinations. Note that the 3μ masses do not have a unique value, and within the statistical and resolution restrictions of the present sample the decay $M \to 3\mu$ is ruled out. The average value of the 3μ mass is $3.4^{+1.5}_{-0.5}$ GeV.

Figure 4(c) shows the projected $M_{\mu^+\mu^-}$ mass combinations. The cross-hatched events correspond to the smaller $\theta_{\mu^+\mu^-}$ opening angle. Note, however, that the distributions are similar and independent of this angle cut. The average value of the $\mu^+\mu^-$ mass for the pairs with $\theta_{\mu^+\mu^-}{}^{\min}$ is $1.6^{+1.0}_{-0.3}$ GeV. The average value of the $\mu^+\mu^-$ mass for the other pair is $1.8^{+1.0}_{-0.4}$ GeV.

One reason for expectation of an L^0 origin of a $\mu^+\mu^-$ pair in each trimuon event is given by the Pais-Treiman bound for these events,[14]

$$0.48 < \langle P_{\mu^-}\rangle / \langle P_{\mu^+}\rangle < 2.1.$$

For the $\mu^+\mu^-$ pairing with the smaller $\theta_{\mu^+\mu^-}$ we find

$$\langle P_{\mu^-}\rangle / \langle P_{\mu^+}\rangle = 1.7 \pm 0.4,$$

consistent with the Pais-Treiman bounds and a pointlike origin of the events.[14] For the symmetic dimuons, chosen by the $\Delta\varphi$ analysis, we find

$$\langle P_{\mu^-}\rangle/\langle P_{\mu^+}\rangle = 1.9 \pm 0.4.$$

The $M_{\mu^+\mu^-}$ mass plot for the symmetric dimuons is shown in Fig. 4(d). The distribution is similar to that for the trimuons in Fig. 4(c). Very crude mass values for the L^0 and M can be obtained from the existing theoretical calculations.[11,15] These are

$$M_{L^0} \simeq 2.0\langle M_{\mu^+\mu^-}\rangle = 3.5^{+1.5}_{-0.4}\ \mathrm{GeV},$$

$$M_M \simeq 2.0\langle M_{\mu^-\mu^-\mu^+}\rangle = 7.0^{+3.0}_{-1.0}\ \mathrm{GeV},$$

and from the $\mu^+\mu^-$ dimuon events we obtain

$$M_{L^0} \simeq 2\langle M_{\mu^+\mu^-}\rangle = 4.9 \pm 1.5.$$

We emphasize that a feature common to all models that seek to explain the properties of trimuon events and symmetric dimuon events will be the inclusion of a neutral lepton—the L^0.

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[1]A. Benvenuti *et al.*, Phys. Rev. Lett. 38, 1110 (1977).

[2]A. Benvenuti *et al.*, Phys. Rev. Lett. 35, 1203 (1975); G. Goldhaber *et al.*, Phys. Rev. Lett. 37, 255 (1976).

[3]A. Benvenuti *et al.*, Phys. Rev. Lett. 35, 1249 (1975); A. K. Mann, in Proceedings of the Eighteenth International Conference on High Energy Physics, Tbilisi, U. S. S. R., July 1976 (to be published); D. Cline, in Proceedings of the American Physical Society Meeting, Division of Particles and Fields, Brookhaven National Laboratory, Upton, New York, 6–8 October 1976 (unpublished).

[4]A. Benvenuti *et al.*, Phys. Rev. Lett. 34, 419 (1975), and 35, 1199 (1975).

[5]We use only events recorded with the high-energy quadrupole-triplet or bare-target neutrino beam at Fermilab.

[6]The basis for the Monte Carlo calculation for charmed-particle production is described in detail by V. Barger and T. Gottschalk (to be published). These calculations follow an extensive phenomenology of charm production by neutrinos carried out by V. Barger, T. Gottschalk and R. J. N. Phillips, University of Wisconsin Report No. COO-881-564, 1977 (to be published).

[7]The first $\Delta\varphi$ distribution for dimuon events was reported in A. Benvenuti *et al.*, Phys. Rev. Lett. 35, 1199 (1975).

[8]O. Fackler, in Proceedings of the American Physical Society Meeting, Division of Particles and Fields, Brookhaven National Laboratory, Upton, New York, 6–8 October 1976 (unpublished).

[9]The 5% estimate is uncorrected for scanning and reconstruction efficiency.

[10]J. von Krogh *et al.*, Phys. Rev. Lett. 36, 710 (1976); C. Baltay, in Proceedings of the American Physical Society Meeting, Division of Particles and Fields, Brookhaven National Laboratory, Upton, New York, 6–8 October 1976 (unpublished); F. A. Nezrick *et al.*, Bull. Am Phys. Soc. 22, 35 (1976); J. F. Grivaz *et al.*, Bull. Am. Phys. Soc. 22, 35 (1976).

[11]There have been previous discussions of a heavy-lepton origin of dimuon events. See, for example, L. N. Chang, E. Derman, and J. N. Ng, Phys. Rev. Lett. 35, 6 (1975); C. H. Albright, Phys. Rev. D 12, 1319 (1975). See also T. C. Yang, DESY Report No. 76/03, 1976 (unpublished).

[12]The possibility of a cascade decay of heavy leptons was first brought to our attention by V. Barger and D. V. Nanopoulos, University of Wisconsin Report No. COO-881-583, 1977 (to be published).

[13]Several recent papers have discussed the possibility of two new massive leptons, for example, T. P. Cheng and L.-F. Li, Phys. Rev. Lett. 38, 381 (1977); B. W. Lee, S. Pakvasa, R. E. Shrock, and H. Sugawara, Phys. Rev. Lett. 38, 937 (1977). See also Ref. 12.

[14]A. Pais and S. B. Treiman, Phys. Rev. Lett. 35, 1206 (1975).

[15]C. H. Albright, B. W. Lee, R. E. Shrock, J. Smith, V. Barger, and D. V. Nanopoulos, private communication.