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Observation of Trimuon Production by Neutrinos

B. C. Barish, J. F. Bartlett, A. Bodek,* K. W. Brown, D. Buchholz,† Y. K. Chu, F. Sciulli, E. Siskind, and L. Stutte‡

California Institute of Technology, Pasadena, California 91125

and

E. Fisk, G. Krafczyk, and D. Nease

Fermi National Accelerator Laboratory, Batavia, Illinois 60510

and

O. Fackler

Rockefeller University, New York, New York 10021

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Two high-energy neutrino events with three muons in the final state are presented. Some examples of possible origins are also discussed.

Neutrino- and antineutrino-induced events with more than one lepton in the final state may well be indicators of the production of massive hadrons with new quantum numbers or of heavy leptons. By now, hundreds of events have been observed[1,2] with two muons in the final state, but no events have been reported with more than two.

We report here on the observation of two neutrino events with three final-state muons. These events were discovered in the data[3] of an experiment to measure the ν and $\bar{\nu}$ total cross sections. This experiment used the Fermilab narrow-band beam,[4] with hadron beam settings over the energy range between 80 and 250 GeV, and with sign selection giving good beam separation of ν_μ and $\bar{\nu}_\mu$. The Caltech-Fermilab neutrino apparatus was used to detect and record the events (see Fig. 1). This detector consisted of an instrumented steel target, with average density $\rho = 4$ g/cm^3, followed by a toroidal spectrometer magnet, with reasonable acceptance for muons of angle $\theta_\mu \leq 100$ mrad in the laboratory. The data sample investigated here contains those events in which at least one muon was observed to traverse the spectrometer magnet. Additional muons were identified in these events by searching for extra tracks in spark chambers imbedded in

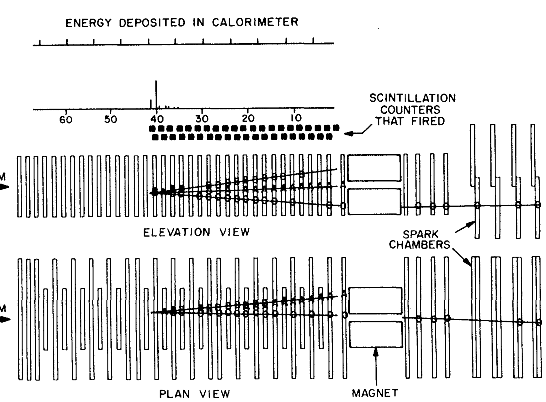

FIG. 1. Trimuon event No. 1. The 5-ft× 5-in. instrumented steel target is followed by the 5-ft.-diam toroidal magnet. In the elevation view, tracks B, A, and O, respectively, proceed vertically downward from the top.

TABLE I. Event samples with at least one muon traversing the spectrometer.

Sample	ν	$\bar{\nu}$	R.E.[b]	A.C.E.[c]
Single μ	12 000	6000	18 000	30 600
($E_h > 63$ GeV)				(3900)
Two μ[a]	41	15	56	94.4
Three μ[a]	2	2	2	2.9

[a]Additional muons are required to penetrate 2.8 m of iron (i.e., $E_\mu > 4$ GeV).
[b]Raw event sample.
[c]Azimuthally corrected event sample.

TABLE II. Kinematic quantities for trimuon events. Vertex parameters calculated assuming that "O," or most energetic particle, is the directly produced muon.

Parameter	Event 1	Event 2
E_h (GeV)	47.3 ± 8.9	105 ± 17
E_O (GeV)	$(-)30.2 \pm 5.4$	$(-)53.9 \pm 14.9$
E_A (GeV)	7.2 ± 1.0	$(+)10.4 \pm 1.2$
E_B (GeV)	5.2 ± 0.5	$(4.0-58.0)$
Q^2 (GeV$^2/c^2$)	6.2 ± 1.8	$(47.0-62.0) \pm 18$
W (GeV)	10.3 ± 0.8	$(13.3-16.3) \pm 1.2$
x	0.06 ± 0.02	$(0.21-0.19) \pm 0.08$
y	0.66 ± 0.05	$(0.69-0.76) \pm 0.07$
p_{TA}[a] (GeV/c)	0.27 ± 0.05	$(0.05-0.05) \pm 0.08$
p_{TB}[a] (GeV/c)	0.33 ± 0.05	$(0.13-2.4) \pm 0.05$
p_{LA}[b] (GeV/c)	0.57 ± 0.09	$(0.57-0.48) \pm 0.17$
p_{LB}[b] (GeV/c)	0.37 ± 0.06	$(0.19-2.1) \pm 0.03$
M_{AB} (GeV/c^2)	0.50 ± 0.05	$(0.32-1.1) \pm 0.05$
x_F	0.21 ± 0.03	$(0.12-0.39) \pm 0.03$

[a]Transverse momenta calculated relative to the direction of the overall hadron system.
[b]Longitudinal momenta calculated in the rest frame of the hadronic final state.

the steel, and requiring that energy deposition in counters imbedded in the steel be characteristic of additional minimum-ionizing particles. In some cases, the additional muons also traversed the toroidal magnet. Muons of energy greater than 4 GeV and with angle relative to the incident neutrino direction typically less than 250 mrad would be found with this procedure.

Table I summarizes the raw event sample for ν and $\bar{\nu}$. The last column gives the corrected number of events after correcting for azimuthal angle losses. The penetration requirement (> 2.8 m steel) suffices to remove background from punch-through of the hadronic shower. This means that the detected extra particles are muons; however, the question remains as to whether these muons result from the decay of π's and/or K's in the hadron shower. We have determined by calculation that second muons from these nonprompt sources are less than 30% of the observed dimuon signal with this penetration cut.[3] Nonprompt sources of trimuons would include (a) simultaneous pion or kaon decay of two hadrons in the shower, and (b) single pion or kaon decay in association with a prompt dimuon event. For our calculated background level, we estimate less than 0.02 events from (a) and less than 0.05 events from (b). Even if *all* dimuon events were from π, K decays, there would be only 0.17 trimuon events expected from these nonprompt decays, whereas two are observed. Other mechanisms, such as muon-pair production from photon and hadron interactions downstream of the neutrino collision, are estimated to contribute less than 0.12 events.[5] It appears unlikely that nonprompt sources account for the observed events.

Both trimuon events were obtained with the narrow-band beam tuned to positive secondaries of mean energy 190 GeV. This means that neutrinos of mean energy 165 GeV (from K decay) and 60 GeV (from π decay) were incident on the apparatus. Figure 1 shows a schematic of one of the events (No. 1) in which one energetic muon (track 0) traversed the toroidal magnet, allowing measurement of its energy (E_0). The direction of bend determines this to be a μ^-, the expected sign for the directly produced muon in a neutrino beam. The second muon (track A) enters the magnet but is not observed to exit; it must, therefore, have substantially lower energy, since it either stopped inside the magnet, or bent through such a substantial angle that it went unobserved in the spark chambers to the rear. The third muon stopped inside the steel target, permitting a total energy measurement (E_B) from its range. The total hadronic energy (E_h) added to these gives a total visible energy, $E_{vis} = 89.9 \pm 9.4$ GeV, considerably lower than that expected for neutrinos from kaon decay. If this neutrino were of kaon origin, then a substantial fraction of its energy would have been carried away by noninteracting neutrals (e.g., neutrinos). It is perhaps more likely that the initiating neutrino is from pion decay; the detailed energy distribution of neutrinos from this source is such that about 10% have observed energies above 90 GeV.

Table II summarizes the measured energies for the two events. For event No. 2, one of the muons exits from the target after depositing 4 GeV of ionization energy and misses the muon spectrometer. This only represents a lower limit on this muon's energy. On the other hand, a total energy of 173 ± 23 GeV is observed in the entire event. We conclude that the initiating neutrino was from kaon decay, and assign an upper limit of 58 GeV (2-standard-deviation level) to track B. It should be noted that both events had the following characteristics: (1) Over half of the observed energy is contained in the hadronic shower energy; (2) roughly 30% of the observed energy is found in the most energetic muon, which also has the sign appropriate (μ^-) to the directly produced muon from neutrino collisions; and (3) the additional muons, when measured, have a small fraction ($\lesssim 10\%$) of the incident neutrino energy.

While it is perhaps premature to speculate on the specific production mechanism of these events from such a small statistical sample, it is worthwhile to compare these events with expected processes. In particular, the characteristics mentioned above would pertain for almost any mechanism in which the primary interaction was of the charged-current inclusive type, and the additional slow muons were associated with the hadronic vertex. In this vein, we have tabulated (Table II) the pertinent kinematic quantities under this assumption and under the further assumption that no large amount of energy is carried away by unseen particles. Both events correspond to rather large invariant mass (W) recoiling against the energetic muon. Indeed, W is close to the maximum obtainable in this energy range with the direct muon traversing the spectrometer magnet.

Some clue to the origin of trimuons may be gleaned from the properties of the two "slow" muons in each event. Table II lists the momenta of the additional muons as observed in the rest system of the hadronic final state (W). (The uncertainty in the energy of one of the muons for event No. 2 is indicated.) These small relative momenta, typically less than 1 GeV, lend further credence to the hypothesis that these muons are associated with the hadronic system.

We do not believe that these small relative energies are necessarily a trivial reflection of the apparatus efficiency. The apparatus in general is better at recognizing muons for *higher* laboratory energies, which correspond, in general, to higher center-of-mass muon energy. Some selection of the perpendicular component of momentum is implicit because of the finite transverse extent of the apparatus. However, in event No. 1, for example, the event would still be recognized with 100% efficiency for laboratory polar angles relative to the direction of the hadron system as much as 4 times larger than those observed. A definitive demonstration of this latter point is only possible with a model assumption, or even better, with many more events.

One possible mechanism for the production of additional muons at the hadronic vertex is the creation of low-mass lepton pairs from virtual photons or the decay of vector mesons. Enhancements at small dimuon mass, and predominantly with a small fraction (x_F) of the available laboratory hadronic energy, have already been observed in hadron-hadron collisions.[6] The values of dimuon mass (M_{AB}) and (x_F) tabulated for these events (Table II) are quite appropriate to such a mechanism.

The observed rate of the three-muon events (2.9/31 000) is similar to the integrated production of dimuon pairs from hadronic collisions (1×10^{-4}). This agreement should be viewed skeptically, however, due to the energy cut implicit in the penetration requirement on each of the additional muons ($E_\mu > 4$ GeV). A more detailed calculation was performed using the explicit dependence on x_F measured in pion-nucleon collisions[7] folded against the hadronic energy distribution of single-muon events in this experiment. The calculation predicts 0.37 events with three muons expected from this source in the experiment, demonstrating the potentially important effect of the minimum 8-GeV energy requirement. Considering (a) the tenuous nature of the assumptions in this calculation (of which the foremost are that pion-induced and neutrino-induced hadronic final states are equivalent) and (b) the statistical level of the data, we cannot conclude whether low-mass μ pairs could be the origin of these events.

Other mechanisms are, of course, possible. For example, assuming some fraction of the dimuon signal were attributable to production of new hadrons (e.g., charm) through charm-changing charged-current production, we might expect associated production of these new hadrons with simultaneous muonic decay to produce trimuon events. The rate for such processes would be smaller than the dimuon rate for two reasons: (a) The associated production is expected to be somewhat smaller than charm-changing production; and (b) there exists an additional factor of the muonic branching ratio. The low muon center-of-mass momenta in Table II are consistent with decaying hadrons in the mass range of 2 GeV.

In summary, we have found two events induced by neutrinos with three muons in the final state. Both events contain an energetic μ^- and two additional muons with low kinetic energy in the hadronic rest frame. Two mechanisms which may contribute to this signal are (1) low-mass muon pairs from virtual photons and/or decay of vector mesons, and (2) associated production of new hadrons which decay leptonically.

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*Now at University of Rochester, Rochester, N. Y. 14627.

†Now at Northwestern University, Evanston, Ill. 60201.

‡Now at Fermilab, Batavia, Ill. 60510.

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[5]The contribution from downstream interactions in the hadronic cascade has been reported for incident 150-GeV pions and protons [K. J. Anderson *et al.*, Phys. Rev. Lett. 37, 799 (1976)]. On the assumption that this production scales to the typically lower-energy hadronic showers discussed here, only 0.12 trimuon events would be expected. J. Pilcher, private communication.

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Search for Muons Produced in Conjunction with the J/ψ Particle*

J. G. Branson, G. H. Sanders, A. J. S. Smith, and J. J. Thaler
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540

and

K. J. Anderson, G. G. Henry, K. T. McDonald,† J. E. Pilcher,‡ and E. I. Rosenberg
Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637
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In a large-acceptance spectrometer at Fermilab, we have searched for multimuon events produced in collisions of 225-GeV/c protons and $\pi^\pm$ mesons with nuclei. In particular, additional muons accompanying the $J/\psi\to\mu\mu$ decay could signal charmed-particle production. For all data combined, the 90%-confidence limit on charmed-particle production in association with the J/ψ is $\sigma_{JC\bar{C}}/\sigma_J<0.01$; the limit on production of J/ψ pairs is $\sigma_{JJ}/\sigma_J<0.021$. Limits are also given for each beam particle separately.

The small width of the J/ψ particle is attractively accounted for[1] if this particle is a bound state of a charmed quark and its antiquark. The Okubo-Zweig-Iizuka (OZI) rule[2] would then predict that the J/ψ may be produced strongly in conjunction with pairs of charmed particles ($C\bar{C}$). On the other hand, should the J/ψ itself carry a new quantum number,[3] then it should be produced in pairs ($J\bar{J}$). Both schemes can be tested by searching for multimuon events resulting from the following processes:

$$\left.\begin{matrix}\pi^\pm\\ p\end{matrix}\right\}+\text{nucleus}\to J/\psi\,(\to\mu^++\mu^-)+(C+\bar{C}\,(\to\mu^\pm+\nu+X))+\text{anything}\,, \qquad (1)$$

and

$$\left.\begin{matrix}\pi^\pm\\ p\end{matrix}\right\}+\text{nucleus}\to J/\psi\,(\to\mu^++\mu^-)+J/\psi\,(\to\mu^++\mu^-)+\text{anything}\,. \qquad (2)$$

We have performed an experiment at Fermilab in which J/ψ's were produced by beams of 225-GeV/c π^+, π^-, and protons incident on carbon and tin targets. They were then detected in the Chicago cyclotron magnet spectrometer via their $\mu^+\mu^-$ decays. The details of the apparatus and the method of data analysis have been reported elsewhere.[4] Briefly, the beam (4 cm×4 cm in size) struck a short nuclear target placed 1.4 m upstream of a 2.2-m-thick iron hadron absorber,