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Observation of a New Process with Trimuon Production by High-Energy Neutrinos

A. Benvenuti, D. Cline, P. Cooper, M. Heagy, R. Imlay, M. E. Johnson, T. Y. Ling, R. Lundy,
A. K. Mann, P. McIntyre, S. Mori, D. D. Reeder, J. Rich, C. Rubbia, R. Stefanski, and D. Winn
Fermilab, Batavia, Illinois 60510, and Department of Physics, Harvard University, Cambridge, Massachusetts 02138, and Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104, and Department of Physics, Rutgers University, New Brunswick, New Jersey 08903, and Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

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We have observed six trimuon events produced by neutrinos in the new large-angle neutrino detector (NEULAND) at Fermilab with the momenta and charges of almost all muons determined. The properties of these events strongly suggest that their origin is not hadronic but may be in the lepton sector.

Multilepton production in high-energy collisions of neutrinos and antineutrinos with nucleons has been observed, and events with both $\mu\mu(\nu)$ and $\mu e(\nu)$ final states have been reported.[1-7] The bulk of these neutrino-induced, oppositely charged dilepton events is now understood to result from the production and weak decay of hadronic matter carrying a new quantum number, presumably charm.[8,9] The explanation of antineutrino-induced, oppositely charged dileptons and of dileptons with the same charge is less clear, but they may signify the existence of new hadronic quantum numbers beyond charm.[10] There have also been earlier searches for ν_μ- and $\bar{\nu}_\mu$-induced events with three charged leptons (trileptons) in the final state.[9,11] In this Letter we report the observation of six trimuon events with the momenta and charges of almost all muons determined. The properties of some of these trimuons strongly suggest that their origin is not hadronic; they are consistent with a leptonlike phenomenon.

The original Harvard-Penn-Wisconsin-Fermilab detector[12] has been substantially modified. The new large-angle detector of neutrino interactions (NEULAND) is depicted in Fig. 1. The three target-detectors have different densities: ~ 8 g/cm^3 for the Fe target (FeT), mass = 250 metric tons; ~ 0.8 g/cm^3 for the pure liquid scintillator calorimeter (LiqC), mass 45 metric tons; and ~ 3 g/cm^3 for the Fe calorimeter (FeC), mass 90 metric tons. Wide-gap optical spark chambers are inserted throughout the LiqC and the FeC to provide visual information about an event. The LiqC and FeC provide timing information and determine the hadronic energy (E_H) deposited in them with uncertainties of less than 15% and 20%, respectively. The 8-m-diam magnetic muon spectrometer, also equipped with wide-gap optical chambers, measures the charge and momentum of wide-angle ($\lesssim$600 mrad) muons of momentum as low as about 3 GeV/c. The 8-m and 4-m spectrometers together provide approximately ± 15% momentum resolution for muons with momentum up to 200 GeV/c.

The data reported here were acquired primarily from a run in which the incident combined neutrino-antineutrino beam was obtained from quadrupole triplet focusing[13] of the secondary hadrons

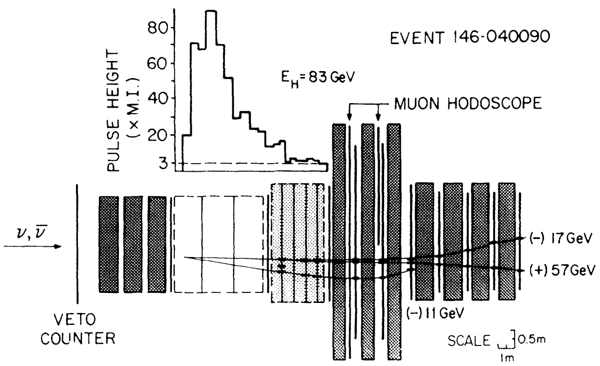

FIG. 1. Schematic outline of the large-angle neutrino detector NEULAND with a trimuon event superimposed on the apparatus.

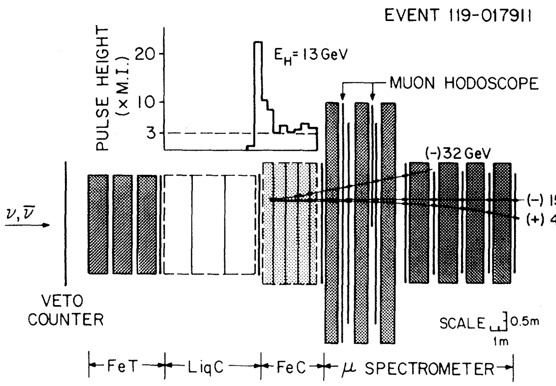

FIG. 2. A particulary interesting trimuon event with three very-high-energy muons with small angles between each pair and a very-low-energy hadron cascade. An hadronic origin for this event is very unlikely.

produced by 400-GeV protons. The observed single-muon ν_μ and $\bar{\nu}_\mu$ relative event rates in that beam are in the approximate ratio 5:1.

Superimposed on the apparatus of Fig. 1 is one of the trilepton events observed in NEULAND. It originated in the second section of LiqC, and exhibits a high-energy hadron cascade which is completely contained in LiqC and FeC. The three muons are observed as a three-times-minimum-ionization signal in the last eight scintillator modules of FeC. Three tracks emerging from a common vertex with small angles between each pair are clearly seen in three spark chambers in FeC, in the corresponding spark chambers in the 8-m spectrometer, and in the first spark chamber of the 4-m spectrometer. Two oppositely charged muons then traverse the entire 4-m spectrometer. Note that the highest-energy muon is positive. Another very striking event is shown in Fig. 2.

Some salient propertites of the six reconstructed trilepton events are given in Tables I and II. It seems reasonable to make a rate comparison with opposite-charge dimuons produced by neutrinos in the same beam *with visible energy greater than 100 GeV.* This is motivated by the observation that $E_{\text{vis}} \gtrsim 100$ GeV for five of the trimuon events. The data give a *raw* ratio $[\text{Rate}(\mu\mu\mu)/\text{Rate}(\mu\mu)]_{E_{\text{vis}}} > 100$ GeV of the order of 5%, with no corrections for relative detection, scanning or reconstruction efficiencies.

There are several possible origins of the trimuon events: (i) accidental space-time coincidence of a dimuon with a muon from a single-muon event, (ii) decay in flight of a pion or kaon in the hadronic cascade of a dimuon event, (iii) direct muon pair production at the hadron vertex, (iv) charm-anticharm production by a neutrino with subsequent semileptonic decay of both the c and $\bar{c}$ particles, (v) sequential semileptonic decays of new hadrons, (vi) flavor-changing weak neutral-current decay of a charmed hadron, (vii) sequential decays of new leptons or leptonlike particles produced at the lepton vertex of the neutrino-nucleon interaction.

TABLE I. Properties of the observed trimuon events.

RUN FRAME	TGT MOD	ENERGY (GeV)		MOMENTUM (GeV)			ANGLE (mrad)			INVAR. MASS (GeV/c^2)			
		E_{vis}	E_H	MU(1)	MU(2)	MU(3)	θ_{12}	θ_{13}	θ_{23}	M_{12}	M_{13}	M_{23}	M_{123}
58 796791	FeT 2	≥ 82	-	(-) 52 ± 7	(-) 20 ± 5	(+)>10	36	29	58	1.2 ±0.4	>0.64	>0.82	>1.6
119 017991	Liq 12	249 ± 25	13 ± 2	(-)157 ± 24	(-) 32 ± 6	(+) 47 ± 8	67	16	77	4.7 ±0.9	1.4 ±0.9	3.0 ±0.5	5.8 ±1.3
126 023729	Liq 6	131 ± 13	61 ±10	(-) 40 ± 6	(-) 6 ± 4	(+) 24 ± 4	204	113	149	3.2 ±1.0	3.5 ±0.5	1.8 ±1.2	5.1 ±1.6
135 031078	FeT 2	≳ 82	-	(-) 57 ± 9	(-) 14 ± 2	(+) 11 ± 6	39	51	24	1.1 ±0.3	1.3 ±0.8	0.3 ±0.2	1.7 ±0.9
138 032717	FeT 3	≳ 48	-	(-) 29 ± 4	(-) 4 ± 1	(+) 15 ± 2	266	110	272	2.9 ±0.3	2.3 ±0.3	2.2 ±0.2	4.3 ±0.5
146 040090	Liq 2	168 ± 15	83 ±12	(-) 17 ± 3	(-) 11 ± 3	(+) 57 ± 7	46	37	68	0.6 ±0.2	1.2 ±0.3	1.7 ±0.4	2.2 ±0.5

TABLE II. Momentum components of the three muons of each trimuon in Table I.

RUN FRAME	MOMENTUM (GeV/c)								
	P_{x1}	P_{y1}	P_{z1}	P_{x2}	P_{y2}	P_{z2}	P_{x3}	P_{y3}	P_{z3}
58[a] 796791	-	-	-	-	-	-	-	-	-
119 017991	2.5 ±0.4	0.79 ±0.2	157 ±24	-0.63 ±0.1	2.0 ±0.5	32 ±6	0.46 ±0.06	-0.45 ±0.07	47 ±8
126 023729	0.18 ±0.07	-3.3 ±0.3	40 ± 6	1.04 ±0.8	0.23 ±0.3	6 ±4	0.51 ±0.14	0.71 ±0.04	24 ±4
135 031078	0.20 ±0.07	0.54 ±0.07	57 ± 9	-0.49 ±0.06	0.08 ±0.07	14 ±2	-0.42 ±0.50	-0.20 ±0.40	11 ±6
138 032717	-0.71 ±0.03	1.10 ±0.02	29 ± 4	0.65 ±0.13	-0.67 ±0.13	4 ±1	-1.40 ±0.3	-0.69 ±0.12	15 ±2
146 040090	0.9 ±0.04	-0.03 ±0.04	17 3	0.74 ±0.14	-0.52 ±0.08	11 ±3	0.85 ±0.08	0.01 ±0.05	57 ±7

[a] Event obtained in test run where 90° stereo view not accurately aligned.

TABLE III. Relative probability estimates of various origins of the observed trimuons per neutrino interaction above 100 GeV. These numbers should be compared with the observed trimuon rate of about 5×10^{-4}.

Possible Source / Event	(ii) π(K) decay in dimuon event[a]	(iii) Direct μ-pair prod. at hadron vertex		(iv) Associated charm production and decay (semileptonic)[e]	(v) Sequential decay of new hadrons[f]
		Continuum[b]	Vector Meson[c,d]		
58 796791	$< 3\times 10^{-6}$	$<10^{-5}$	-	$<8\times 10^{-6}$	$<8\times 10^{-6}$
119 017991	3×10^{-7}	10^{-9}	$\varphi(<10^{-6})$ $J/\psi(\lesssim 2\times 10^{-7})$	5×10^{-9}	8×10^{-9}
126 023729	5×10^{-5}	2×10^{-8}	$\varphi(<10^{-6})$ $J/\psi(\lesssim 2\times 10^{-7})$	10^{-6}	8×10^{-6}
135 031078	2×10^{-6}	$<3\times 10^{-5}$	ρ,φ,ω (7×10^{-6})	$<10^{-5}$	$<2\times 10^{-5}$
138 032717	9×10^{-6}	2×10^{-7}	-	$<2\times 10^{-5}$	$<3\times 10^{-5}$
146 040090	1×10^{-5}	2×10^{-7}	ρ,φ,ω (7×10^{-6})	3×10^{-7}	3×10^{-6}

[a] Estimated using $P=10^{-2}f(z)\lambda_{\text{abs}}/\lambda_{\text{decay}}$, where $f(z)=2e^{-8z}$ is the probability (Ref. 14) of producing a π^- with $E_{\pi^-}/\nu \geqslant z$ and ν is the total hadronic energy. We use $z=E_{\mu^-}/(E_{\mu^+}+E_{\mu^-}+E_H)$. The yield of μ^- from K^- decay is smaller than that from π^- decay by a factor of ~ 3.

[b] The numbers in the table represent the probability of obtaining a μ pair from a virtual W^+ nucleon collision with mass $M_{\mu\mu}$ and Feynman x variable (x_F) greater than the values measured for that event. We have used the measured distribution in $M_{\mu\mu}$ and cross section for the process π + nucleon $\rightarrow \mu^-\mu^+$ + anything (Refs. 15 and 16) parametrized in the form $Ed^3\sigma/dp^3=A(1-x_F)^c e^{-bp_\perp}$ integrated over all $p_\perp$. Note, however, that for the events observed in Ref. 15 $\langle p_\perp\rangle \approx 0.5$ GeV/c, while $\langle p_\perp\rangle$ for the trimuon events is ≈ 2 GeV/c. The $\mu^-\mu^+$ combination with the larger probability is given.

[c] Ref. 14.

[d] Ref. 16.

[e] The upper limit due to associated charm production is given by $P=\alpha[B(c\rightarrow\mu+\text{anything})]^2 f(z_+)f(z_-)$, where $\alpha\equiv\sigma(\nu N\rightarrow\mu^- c\bar{c}X)/\sigma(\nu N\rightarrow\mu^- X)$. The branching ratio $B[c(\bar{c})\rightarrow\mu+\text{anything}]$ was assumed to be 0.1; and an upper limit of 10^{-2} was taken for α from the observed fraction of same-sign dimuons! The form of $f(z)$ was assumed the same as for pions (see Ref. a above).

[f] Here $P=\beta\, B(c'\rightarrow c+\mu+\text{anything})\, B(c\rightarrow\mu+\text{anything})\times G(z)$, where $\beta=\sigma(\nu N\rightarrow\mu^- c'X)/\sigma(\nu N\rightarrow\mu^- X)\lesssim 10^{-1}$. The branching ratios are assumed to be 0.1. The factor $G(z)$, the probability of obtaining the μ^- and μ^+ with energies greater than those observed, is calculated assuming c' is produced with the same $\bar{z}$ distribution as that for pions, a three-body decay of c' into $c\mu\nu$, and a uniform energy spectrum of muons from c decay.

We have estimated for each event in Table I the relative probability that it arises through each of the origins (i) to (v) above. Straightforward probability calculations lead to the conclusion that (i) has negligible probability ($\approx 10^{-8}$ per neutrino event). The estimates for origins (ii) to (v) are given in Table III. From the small rates shown in Table III we conclude that these sources are improbable explanations of the six trimuons.

It should be emphasized that the origins (i) to (v), either individually or collectively, cannot be appreciably more probable than our estimates indicate because large numbers of trimuons with greater probabilities than those for the events in Table I should then have been observed from one or more of those origins. It is, however, unlikely that significant numbers of trimuons are being missed in NEULAND. Hence actual rates (i) to (v) are less than the upper limits in Table III.

Assuming some flavor-changing weak neutral currents are present in nature (although there is preliminary evidence in the failure to observe D^0-$\bar{D}^0$ mixing[9] that suggests otherwise), we estimate that it is kinematically very unlikely that a D^0 can be produced with sufficient energy to account for the lowest-total-energy $\mu^+\mu^-$ pair in each of the trimuon events from (vi).

The estimates above strongly suggest that origins which involve either old or new hadron production and decay, singly, in pairs, or sequentially, are very unlikely to be the sources of all the trimuon events in Table I, since the total estimated upper limit of all the processes in Table

III combined is 2.4×10^{-4} per neutrino event, of which 1.9×10^{-4} arises from three of the trimuon events (126, 135, and 138) and only 0.5×10^{-4} is attributable to the other three events (58, 119, and 146). Another possibility (vii) is that those trimuons arise at the lepton vertex of the neutrino-nucelon interactions, perhaps from the production of a massive new lepton (M) which decays to a muon, an antineutrino and a lighter, new lepton (L), which in turn decays to two muons and a neutrino.[17] We plan to discuss the evidence for that possibility subsequently, and to include additional evidence from ν_μ-induced symmetric dimuons, i.e., those satisfying locality bounds.[18]

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Spontaneous Breakdown of Muon-Number Conservation and Off-Diagonal Neutral Currents*

M. A. B. Bég
The Rockefeller University, New York, New York 10021

and

A. Sirlin
New York University, New York, New York 10003

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We suggest that the conservation of muon number is associated with a local gauge principle and that small nonconservation effects develop from the spontaneous breakdown of the gauge symmetry. Experimental consequences of the scheme, stemming from the spontaneous genesis of off-diagonal neutral currents, are discussed in detail.

In this Letter we suggest that the conservation of muon number is associated with a local gauge principle and that small nonconservation effects develop from the spontaneous breakdown of this gauge symmetry. To implement this suggestion, in the framework of a unified description of weak and electromagnetic interactions,[1] we enlarge the Weinberg-Salam (W-S) gauge group to $\mathrm{U}(1)\otimes\mathrm{U}(1)\otimes\mathrm{SU}(2)$, the extra U(1) corresponding to muon number. The requirement of renormalizability forces us to endow fields other than the muon and its neutrino with muon number; we choose these fields to be the strangeness- and charm-bearing quark fields. (The muon number that must be allotted to these hadron fields is $-\frac{1}{3}$.) The nonconservation of charm, strangeness, and muon number then appears as cognate phenomena, albeit characterized by different magnitudes. Off-diag-