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OBSERVATION OF A NEW PROCESS WITH TRIMUON PRODUCTION BY HIGH ENERGY NEUTRINOS*

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Abstract

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.

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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 note 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 lepton-like phenomenon.

The original HPWF detector[12] has been substantially modified and now consists of three separate target-detectors and two large magnetic spectrometers. This new large angle detector of neutrino interactions (NEULAND) is depicted in Fig. 1. The three target-detectors have different densities: $\approx 8\ \mathrm{gm/cm^3}$ for the 3 sections of the Fe target (FeT), total mass = 250 metric tons; $\approx 0.8\ \mathrm{gm/cm^3}$ for the 12 sections of the pure liquid scintillator calorimeter (LiqC), total mass 45 metric tons; and $\approx 3\ \mathrm{gm/cm^3}$ for the 10 sections of the Fe calorimeter (FeC), total mass 90 metric tons. As shown in Fig. 1, 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; single, double and triple muon states in which the muons traverse more than 8 calorimeter sections are distinguished from one another with 95% confidence.

The 8 m diameter 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 $\pm$15% momentum resolution for muons with momentum in the region 100 to 200 GeV/c. A large area, 35 cm x 35 cm grid, liquid scintillation counter hodoscope in the 8 m spectrometer, and large area scintillation counters in the 4 m spectrometer furnish trigger requirements for one and two muon final states. Other triggers based on a minimum energy deposition in LiqC or FeC in conjunction with a downstream muon count were also used.

The data reported here were acquired in part from a test run (Nov. 1976) and in part from a run dedicated to this experiment (Dec. 1976). In both runs the incident combined neutrino-antineutrino beam was obtained from quadrupole triplet focusing[13] of the secondary hadrons 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. For most of the dedicated, high intensity run the beam spill duration was between 2 and 10 msec.

Superimposed on the apparatus of Fig. 1 is one of the trilepton events observed in NEUIAND. 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 3 times minimum ionization signal in the last eight scintillator modules of FeC. Muon tracks are not observed in some of the upstream spark chambers because those chambers were not operating during part of the run, but three tracks 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. The LiqC and FeC, as well as the hodoscope, show the three muons to be in time

coincidence within ≈ 200 ns. The tracks of the three muons project back to a common vertex within an uncertainty of 20 cm determined by multiple scattering and measurement error. Another very striking event with three very high mumentum muons, again with small angles between each pair, is shown in Fig. 2. Note particularly the low value of E_H for this event and the 3 times minimum ionizing signal throughout FeC.

Some salient properties of the six reconstructed trilepton events are shown in Tables I and II. Observe that three of these events occur in FeT, two in LiqC and one (119) at the boundary between LiqC and FeC. The absence of events from FeC is partly due to trigger requirements and partly statistical. The lowest visible energy of the three events for which E_H is available is 131 GeV, and the lowest visible energy of any event is 48 GeV. In four of the events all muons have momenta greater than or equal to 10 GeV/c, and the angle between any two muons is less than 5 degrees. It is difficult to specify the rate of trimuon production accurately because the detection and reconstruction efficiencies are as yet uncertain, and we do not know the visible energy distribution of trimuons. However, it seems reasonable at this time to make a rate comparison with opposite charge dimuons produced by neutrinos in the same beam with visible energy greater than 100 GeV. The data give a raw ratio $[\mathrm{Rate}(\mu\mu\mu)/\mathrm{Rate}(\mu\mu)]_{E_{vis} > 100\ \mathrm{GeV}}$ 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 similar to the yield of prompt muon pairs observed in hadron-hadron collisions, (iv) charm-anticharm

production by a neutrino in a weak charged current interaction with subsequent semileptonic decay of both the c and $\bar{c}$ particles, (v) sequential semileptonic decays of new hadrons, i.e., production of a new hadron and its semileptonic decay to another new hadron which also decays semileptonically, (vi) flavor changing weak neutral current decay of a charmed hadron, (vii) sequential decays of new leptons or lepton-like particles produced at the lepton vertex of the Feynman diagram describing the neutrino-nucleon interaction.

We have estimated for each event in Table I the probability that it arises through each of the origins (i) to (v) above. These estimates are given in Table III. Origins (i) and (ii) involve straightforward probability calculations which lead to the conclusion that (i) has negligible probability ($\approx 10^{-8}$ per single muon event) and (ii) is a very improbable explanation of 5 of the 6 trimuon events. To estimate (iii) we assume that the π-nucleon and p-nucleon collisions from which prompt muons arise are simulated by the virtual W^+-nucleon collision in neutrino interactions, at least at not too large values of the invariant mass $M_{\mu\mu}$ of the produced muon pair. We use recent data which show that 0.7 ± 0.2 of all observed prompt muons are part of a $\mu^+\mu^-$ pair[14], and also use the measured distribution in invariant mass $M_{\mu\mu}$ for such pairs.[15] Table III shows that (iii) is very unlikely to be the explanation of more than two trimuon events.

In calculating (iv) we have taken the upper limit on the cross section ratio, $\sigma(\nu_\mu + N \rightarrow \mu^- + c + \bar{c} + X)/\sigma(\nu_\mu + N \rightarrow \mu^- + X) \leqslant 10^{-2}$, on the basis of the observed fraction of same sign dimuons in neutrino interactions.[1] Then semileptonic decay branching ratios and production and decay kinematics lead to the probability values in Table III. We conclude that (iv) is an unlikely explanation of any of the six trimuons. Qualitatively similar arguments apply to the sequential decays of new hadrons (v) and lead to the small probabilities given in Table III.

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^o-$\bar{D}^o$ mixing that suggests charm changing--as well as strangeness changing--neutral currents may in fact be absent), we estimate the probability of producing, say, a D^o with sufficient energy to account for the lowest total energy $\mu^+\mu^-$ pair in each of the trimuon events (vi). We conclude that kinematically (vi) is unlikely to be the origin of all of the trimuon events, even if some flavor changing weak neutral current were to have the same strength as the known flavor conserving weak neutral current.

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 we observe 6 events with an estimated upper limit of less than one event. Another possibility (vii) is that those trimuons arise at the lepton vertex of the neutrino-nucleon interaction, perhaps from the production of a massive new lepton which decays to a muon, an antineutrino and a lighter, different, massive new lepton, which in turn decays to two muons and a neutrino. 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 the bounds[16] $0.48<p_{\mu^-}/p_{\mu^+}<2.1$.

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FIGURE CAPTIONS

Fig. 1. Schematic outline of the large angle neutrino detector NEULAND with a trimuon event superimposed on the apparatus. The scintillation counters in the 4 m spectrometer and the partitioning of LiqC and FeC are not shown.

Fig. 2. A particularly 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.

TABLE I

Properties of the Observed Trimuon Events

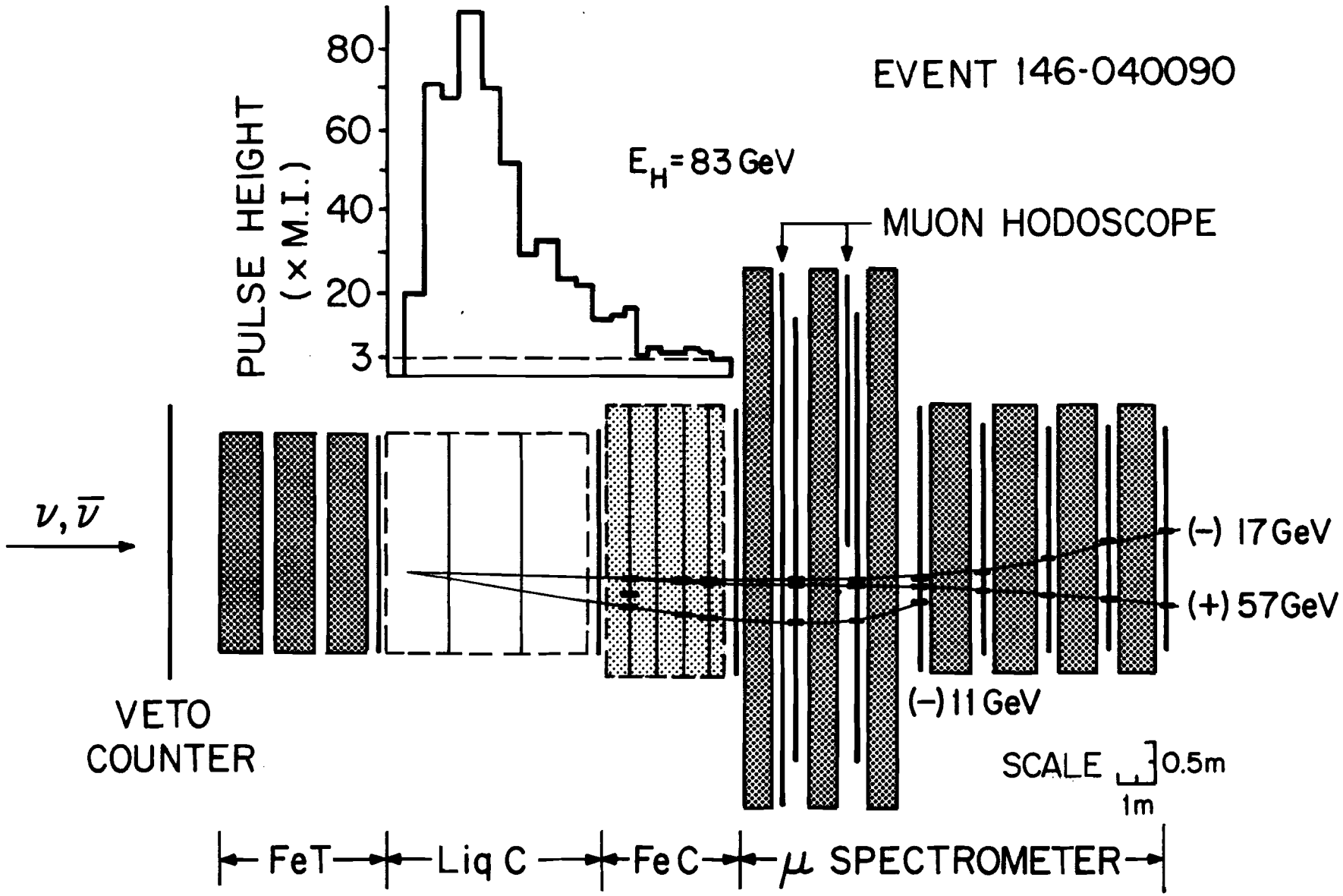
RUN FRAME	TGT MOD	ENERGY (GeV)		MOMENTUM (GeV/c)			ANGLE (mrad)			INVAR. MASS (GeV/c^2)			
		E_{vis}	E_H	MU(1)	MU(2)	MU(3)	θ_{12}	θ_{13}	θ_{23}	M_{12}	M_{13}	M_{23}	M_{123}
58 796791	FeT 2	≥ 92	-	(+)≥10	(-) 52 ± 5	(-) 20 ± 5	29	58	36	≥0.64	≥0.82	1.16 ±	≥1.6
119 017991	Liq 12	250 ± 17	13 ± 2	(-)157 ± 16	(-) 32 ± 6	(+) 47 ± 2	67	16	77	4.7 ±0.2	1.4 ±0.2	3.0 ±0.2	5.8 ± 0.4
126 023729	Liq 6	131 ± 12	61 ± 10	(+) 24 ± 2	(-) 40 ± 3	(-) 6 ± 4	113	149	204	3.5 ±0.1	1.8 ±1.0	3.2 ±0.6	5.0 ±1.2
135 031078	FeT 2	≥ 75	-	(-) 57 ± 3	(-) 14 ± 1	(+) 11 ± 6	39	51	24	1.1 ±0.1	1.3 ±0.9	0.3 ±1.5	1.7 ±1.7
138 032717	FeT 3	≥ 48	-	(-) 29 ± 0.7	(+) 15 ± 2.2	(-?) 4 ± 0.9	110	266	272	2.3 ±0.2	2.9 ±0.1	2.1 ±0.2	4.3 ±0.4
146 040090	Liq 2	163 ± 14	83 ± 12	(-) 17 ± 1	(+) 57 ± 2	(-) 11 ± 3	37	46	68	1.2 ±0.1	0.64 ±0.3	1.7 ±0.2	2.2 ±0.4

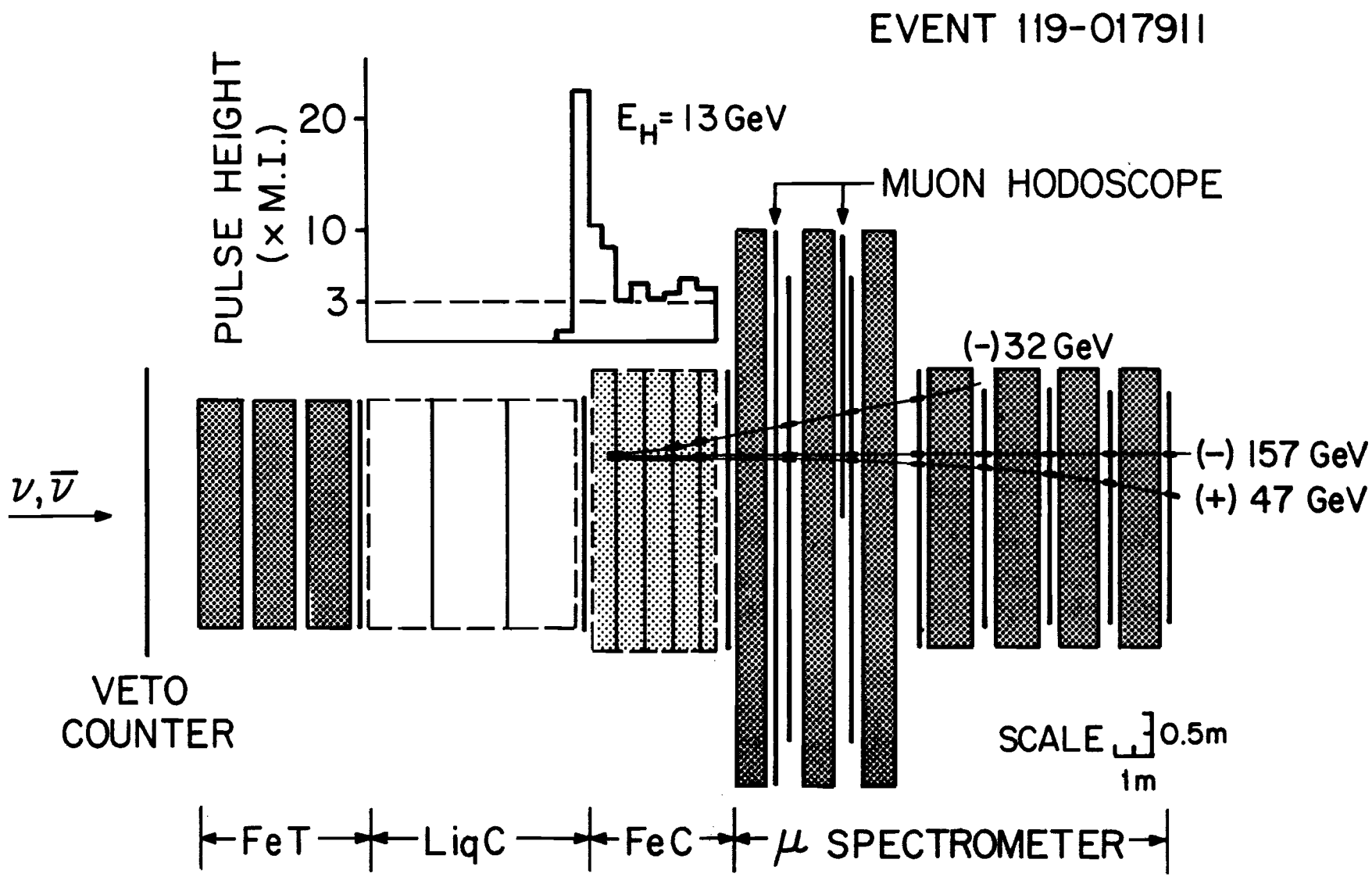
Table II. Momentum Components of the Three Muons of Each Trimuon in Table I.

RUN FRAME	MOMENTUM (GeV/c)								
	P_{x1}	P_{y1}	P_{z1}	P_{x2}	P_{y2}	P_{z2}	P_{x3}	P_{y3}	P_{z3}
58 796791									
119 017991	2.5 ±0.4	0.79 ±0.2	157 ±16	-6.3 ±0.1	2.0 ±0.5	32 ±6	0.46 ±0.06	-0.45 ±0.07	47 ±2
126 023729	0.18 ±0.07	-3.3 ±0.3	40 ± 3	1.04 ±0.8	0.23 ±0.3	6 ±4	0.51 ±0.14	0.71 ±0.04	24 ±2
135 031078	0.20 ±0.07	0.54 ±0.07	57 ± 3	-0.49 ±0.06	0.08 ±0.07	14 ±1	-0.42 ±0.50	-0.20 ±0.40	11 ±6
138 032717	-0.71 ±0.03	1.10 ±0.02	29 ± 1	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 0.8	0.74 ±0.14	-0.52 ±0.08	11 ±3	0.85 ±0.08	0.01 ±0.05	57 ±2

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 0.5×10^{-3}.

Possible Source / Event	(ii) π(K) decay of dimuon event[a]	(iii) Direct μ-pair prod. at Hadron Vertex		(iv) Associated Charm Production and Decay (Semi-Leptonic)	(v) Sequential Decay of New Hadron (c,b..)
		Continuum	Vector meson $\rho\omega\varphi J$		
58 796791	$<3 \times 10^{-6}$	$<10^{-5}$		7×10^{-6}	7×10^{-6}
119 017991	3×10^{-7}	$\leqslant 6 \times 10^{-8}$	$\varphi(<10^{-6})$ $J/\psi(\sim 3 \times 10^{-7})$	3×10^{-7}	3×10^{-7}
126 023729	5×10^{-5}	$\sim 3 \times 10^{-7}$	$\varphi(<10^{-6})$ $J/\psi(-3 \times 10^{-7})$	10^{-5}	1.4×10^{-5}
135 031078	2×10^{-6}	$\sim 10^{-4}$	$\rho\varphi\omega(7 \times 10^{-6})$	1.4×10^{-5}	1×10^{-5}
138 032717	9×10^{-6}	$\lesssim 10^{-7}$	-	10^{-5}	10^{-5}
146 040090	1×10^{-5}	$\sim 1.5 \times 10^{-5}$	$\rho\varphi\omega(7 \times 10^{-6})$	4×10^{-6}	4×10^{-6}


EVENT 146-040090
PULSE HEIGHT (× M.I.)
80
60
40
20
3
E_H = 83 GeV
MUON HODOSCOPE
$\nu, \bar{\nu}$
VETO COUNTER
(−) 17 GeV
(+) 57 GeV
(−) 11 GeV
SCALE
0.5m
1m
FeT
Liq C
Fe C
μ SPECTROMETER


EVENT 119-017911
PULSE HEIGHT (x M.I.)
20
10
3
E_H = 13 GeV
MUON HODOSCOPE
(-)32 GeV
(-) 157 GeV
(+) 47 GeV
$\nu, \bar{\nu}$
VETO COUNTER
SCALE
0.5m
1m
FeT
LiqC
FeC
μ SPECTROMETER