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OBSERVATION OF A NEUTRINO EVENT WITH FOUR ENERGETIC MUONS

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1. The event

We report here an event produced by neutrinos in which four energetic muons are emitted. Several groups¹⁾ have reported on events with up to three energetic muons in the final state, produced in neutrino beams of high energy. To our knowledge this is the first clear four-muon event reported.

The event was recorded in an exposure of the CDHS detector to a wide-band neutrino beam at the CERN-SPS. The detector²⁾ combines the function of target (fiducial mass ~ 570 tons), hadron shower calorimeter and muon spectrometer integrally in 19 basically similar modules. Each module consists of 15 or 5 iron plates 3.75 meters in diameter with a total thickness of 75 cm of iron and a weight of 65 tons. The hadron shower is measured by means of scintillation counters between the iron plates, and the muon trajectories are measured in triple plane drift chambers between the modules. The information about the event consists of the total hadronic energy, and the momenta and angles of all the muons emitted. A minimum range requirement for four traversed modules, corresponding to about 4.5 GeV, has been imposed for each of the muons.

The event was found in a search for ≥ 2 muon events in the wide-band beam. The data sample was confined to events with a vertex between modules 2 and 13, and with a radial vertex position less than 1.6 meters.

The incident neutrinos were produced by the decay of positive secondaries from the interaction of 350 GeV protons on a Be target. The focusing was achieved using a horn and reflector downstream of the target (negative secondaries were defocused).

The computer reconstruction of the four-muon event is shown in Fig. 1. The relevant measured parameters are listed in Table I.

II. Rate

The event is the only four-muon event observed by us so far. The total exposure corresponds to a flux produced by 0.9×10^{18} protons on target. In the same exposure $\sim 3 \times 10^6$ single muon events, $\sim 7 \times 10^3$ opposite sign dimuon events, and 35 trimuon³⁾ events have

been produced in the detector^{*)}. The rate corresponding to the four-muon event relative to the opposite sign dimuon events is thus $\sim 1.4 \times 10^{-4}$.

Figure 2 shows a calculation of the expected energy spectrum for charged current events⁴⁾ (assuming a linearly rising total cross-section), together with the expected $\bar{\nu}$ contamination. According to the calculation, the ratio of $\bar{\nu}$ events to ν events is expected to be $\sim 5\%$ above 30 GeV neutrino energy. For comparison, the spectrum for a charged current event sample is included in Fig. 2.

III. Background

The most substantial background is due to trimuons with an extra muon from $\pi^+ \rightarrow \mu^+$ or $K^+ \rightarrow \mu^+$ decay in the shower. The expected number of such background events can be calculated on the basis of the known number of trimuon events and their accompanying hadron energy. The average hadron energy is 28 GeV³⁾ leading to an expected number of $(1.2 \pm 0.4) \cdot 10^{-2}$ events, which though small, is not negligible.

IV. Possible origins of the event

We list here some possible mechanisms for producing four muons; the first three do not require new types of particles.

- 1) Charm production by the GIM weak current⁵⁾ as in the case of normal dimuon events^{6,7)}, together with radiative production of a muon pair by the muon (Fig. 3a).
2. Charm production as in 1), together with the production of a muon pair in the hadron shower (Fig. 3b)^{**)} .
- 3) Charm production as in 1) and 2), together with a charm pair production in the hadron shower (Fig. 3c).
- 4) Mechanisms requiring new particles, including the following:
a) quarks with new flavours, b) new heavy leptons, or c) a combination of both. In each of these processes four-muon events arise from the weak decay cascade of the new particles.

*) The single muon and dimuon rates are estimated on the basis of a sample.

**) Processes 1) and 2) should, in principle, be considered together since they interfere⁸⁾. We prefer to list them separately for conceptual reasons.

For the sum of processes 1) - 3) the rates are estimated to be of the order of 3×10^{-5} relative to the dimuon rate. Herein the radiative μ -pair production has been estimated by Barger et al.⁸⁾, and the hadronic production was calculated using the data of Anderson et al.⁹⁾ and the assumption that the interaction of a virtual W resembles a pion interaction.

Processes 2) and 3) share the property that one of the two negative muons is associated with the lepton vertex, and the other three muons are associated with the hadron shower, and are expected to have relatively small transverse momenta with respect to it. These transverse momenta are listed in Table II for the two choices of leading muon. The rather large values of transverse momenta for either choice would seem to favour either process 1) or 4b) and 4c) but are not very probable for the mechanisms 2), 3) and 4a) for muons originating in the shower. However, on the basis of this single event it is not possible to rule out any of these possibilities.

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FIGURE CAPTIONS

- Fig. 1 : Four-muon event as computer reconstructed.
- a) On top, pulse heights; next lower, horizontal drift chamber hits and scintillator hits. Bottom, drift chamber hits in views $\pm 60^\circ$ to horizontal.
 - b) Drift chamber hits projected into the plane normal to the neutrino direction.
- Fig. 2 : Total visible energy spectrum as observed for single μ events. The full line gives the expected ν energy spectrum of Ref. 4. The dotted line gives the $\bar{\nu}$ contamination.
- Fig. 3 : Some processes which give rise to four-muon events.

TABLE I

Measured quantities of the four muon event.

1.	Total observed energy				91.4 ± 7.3 GeV
2.	Hadron shower energy				58 ± 7 GeV
3.	Momenta of the muons (GeV/c) ^{*)}	P_x	P_y	P_z	
	Muon 1 (+)	0.50	0.20	11.1	
	Muon 2 (-)	-1.52	-1.69	8.4	
	Muon 3 (+)	-0.93	-1.12	9.0	
	Muon 4 (-)	-0.24	-0.63	4.45	
4.	Muon masses, pair-wise ^{*)}				
	Muons 1 and 2				3.0 GeV
	Muons 1 and 3				2.1 GeV
	Muons 1 and 4				1.3 GeV
	Muons 2 and 3				0.95 GeV
	Muons 2 and 4				0.87 GeV
	Muons 3 and 4				0.40 GeV
5.	Three muon masses ^{*)}				
	Muons 1, 2 and 3				3.8 GeV
	Muons 1, 2 and 4				3.4 GeV
	Muons 2, 3 and 4				1.3 GeV
	Muons 1, 3 and 4				2.5 GeV
6.	Four muon invariant mass				4.1 GeV

^{*)} The momenta and the masses have the following errors due to multiple scattering and measurement: $\Delta p/p = 0.12$;

$$\Delta M_{\mu\mu}/M_{\mu\mu} = 0.12; \Delta M_{\mu\mu\mu}/M_{\mu\mu\mu} = 0.16; \Delta M_{\mu\mu\mu\mu}/M_{\mu\mu\mu\mu} = 0.20.$$

TABLE II

Transverse momenta with respect to the hadron shower direction for the three non-leading muons.

Leading Muon	$P_{TSH,1}$	$P_{TSH,2}$	$P_{TSH,3}$	$P_{TSH,4}$
2	0.29	--	1.71	0.80
4	0.48	2.33	1.52	--

FIG.1

FIG. 2

(a)

(b)

(c)

FIG.3