PHYSICAL REVIEW LETTERS

VOLUME 41 | 11 SEPTEMBER 1978 | NUMBER 11

Evidence for the Production of Prompt Like-Sign Dimuon Events by High-Energy Neutrinos

A. Benvenuti,[a] F. Bobisut,[b] D. Cline, P. S. Cooper, M. G. D. Gilchriese, S. M. Heagy, R. Imlay, M. Johnson, T. Y. Ling, R. Lundy, A. K. Mann, P. McIntyre, S. Mori, D. D. Reeder, J. Rich, R. Stefanski, and D. R. Winn

Fermi National Accelerator Laboratory, Batavia, Illinois 60510, and Department of Physics, Harvard University, Cambridge, Massachusetts 02138, and Department of Physics, Ohio State University, Columbus, Ohio 43210, 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 Wisconisn, Madison, Wisconsin 53706

(Received 30 May 1978)

We report the observation of 46 $\mu^-\mu^-$ events in high-energy neutrino-nucleon collisions at Fermilab. Measurement of the production rate of the $\mu^-\mu^-$ events relative to that of $\mu^-\mu^+$ events in targets of different hadronic absorption lengths give $N^{\rm prompt}(\mu^-\mu^-)/N^{\rm prompt}(\mu^-\mu^+) = 0.06 \pm 0.05$ for $p_\mu > 5$ GeV/c, and 0.12 ± 0.05 for $p_\mu > 10$ GeV/c. The properties and possible origins of these events are discussed.

The subject of dimuon production by high-energy neutrinos and antineutrinos has been of considerable interest since its discovery.[1] More recent experiments[2] have confirmed the earlier observation and supported the interpretation of the opposite-sign dimuon events ($\mu^-\mu^+$) as evidence for a new hadronic quantum number—charm.[3,4] However, the nature and the origin of the observed like-sign dimuon events ($\mu^-\mu^-$, $\mu^+\mu^+$) remain unknown. A consequence of the smaller observed rate for these events is that the background due to the decay in flight of pions and kaons from ordinary deep-inelastic neutrino events may account for a large fraction, if not all, of the events observed. It is important to determine whether "prompt" like-sign events exist, because the rate and nature of prompt $\mu^-\mu^-$ events would provide important clues to the understanding of another facet of multimuon phenomena, namely, the recently discovered trimuon events.[5] We report in this Letter the result of measurements, using a data sample of about seven times our previous statistics,[4] of the relative rate $N(\mu^-\mu^-)/N(\mu^-\mu^+)$ in targets of different hadronic absorption lengths, which suggest the presence of a prompt $\mu^-\mu^-$ signal.

The apparatus for this experiment was described in detail elsewhere.[5] Briefly, the target detector consists of three parts of different density, an iron target (FeT), a liquid-scintillator calorimeter (Liq$C$) and an iron-plate calorimeter (FeC). The effective hadronic absorption lengths and fiducial masses for each of the three targets are listed in the first two columns of Table I.

The data reported here were acquired at Fermilab in three runs, using a quadrupole triplet (QT) and sign-selected bare-target beams (SSBT), with 400-GeV incident protons. The characteristics of these beams and the numbers of useful protons on target were summarized in a previous Letter.[6] The QT and SSBT(ν) runs yielded 199 $\mu^+\mu^-$ and 46 $\mu^-\mu^-$ events, predominantly ν_μ in-

TABLE I. Numbers of observed dimuon events and calculated numbers of dimuons from pion and kaon decays in the three targets. Also shown are the fiducial masses and effective absorption lengths for the three targets. These absorption lengths include the spacings within each target and the end effects for each target.

Target	Fiducial mass (tons)	Abs. length (cm)	$N^{obs}(\mu^-\mu^+)$ $p_\mu > 5$ GeV	$N^{obs}(\mu^-\mu^+)$ $p_\mu > 10$ GeV	$N^{decay}(\mu^-\mu^+)$ $p_\mu > 5$ GeV	$N^{decay}(\mu^-\mu^+)$ $p_\mu > 10$ GeV	$N^{obs}(\mu^-\mu^-)$ $p_\mu > 5$ GeV	$N^{obs}(\mu^-\mu^-)$ $p_\mu > 10$ GeV	$N^{decay}(\mu^-\mu^-)$ $p_\mu > 5$ GeV	$N^{decay}(\mu^-\mu^-)$ $p_\mu > 10$ GeV
Iron (Fe*T*)	198	31	75	50	11.7	3.1	12	8	8.1	1.9
Iron cal. (Fe*C*)	42	61	42	23	11.1	2.3	10	4	7.8	1.8
Liq. cal. (Liq*C*)	36	120	56	32	23.5	6.9	16	6	16.3	3.8
	Total		173	105	46.3	12.3	38	18	31.7	7.5

duced. The SSBT($\bar{\nu}$) run yielded 49 $\mu^+\mu^-$ and 2 $\mu^+\mu^+$ events, mostly produced by $\bar{\nu}_\mu$.

The relative rates $R(\mu^-\mu^-)/R(\mu^-)$ in each target are difficult to determine because of differences in acceptance and trigger requirements between dimuons and single-muon events. However, the ratio $N(\mu^-\mu^-)/N(\mu^-\mu^+)$ was verified to be independent of these systematic effects, for to a good approximation these effects were the same for both the $\mu^-\mu^-$ and $\mu^-\mu^+$ events. The observed numbers of dimuon events from each target are listed in Table I. The ratios $N^{obs}(\mu^-\mu^-)/N^{obs}(\mu^-\mu^+)$ plotted against hadronic absorption length are shown in Figs. 1(a) and 1(b) for muon momentum cuts $p_\mu > 5$ and 10 GeV/c, respectively. To simplify the interpretation, the fraction of $\mu^-\mu^+$ events due to pion and kaon decays should be subtracted from $N^{obs}(\mu^-\mu^+)$. This background, listed in Table I in the column labeled $N^{decay}(\mu^-\mu^+)$, is obtained from a calculation which uses among other data momentum spectra and multiplicities of charged pions and kaons measured in neutrino interactions. The ratios $N^{obs}(\mu^-\mu^-)/N^{prompt}(\mu^-\mu^+)$ obtained after this correction should then exhibit only the dependence on absorption length of the observed $\mu^-\mu^-$ events. This is shown in Figs. 1(c) and 1(d). Linear fits to the data, with both the slope and intercept as free parameters, are also shown.

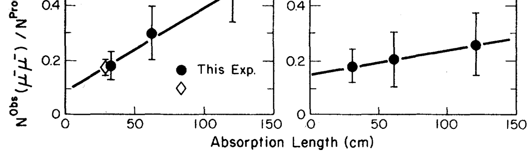

FIG. 1. Ratios of the number of observed $\mu^-\mu^-$ events to $\mu^-\mu^+$ events in three targets of different hadronic absorption lengths for (a) $p_\mu > 5$ GeV and (b) $p_\mu > 10$ GeV. Also shown are ratios of the number of observed $\mu^-\mu^-$ events to the number of ***prompt*** $\mu^-\mu^+$ events vs hadronic absorption length for (c) $p_\mu > 5$ GeV (◇, data from Ref. 8) and (d) $p_\mu > 10$ GeV. The straight line is a linear fit to the data of this experiment.

We observe that (i) the decay of pions and kaons account for a significant fraction of the $\mu^-\mu^-$ events for the case $p_\mu > 5$ GeV/c; (ii) the fitted slope decreases by a factor of about 4 as the minimum momentum cut of the muons is raised from 5 to 10 GeV/c. This factor of 4, which results from the reduction of pion and kaon background as the momentum cutoff is increased, is verified in our detailed calculation of pion and kaon decay. Note that the fitted slopes empirically determine the pion- and kaon-decay contributions to the $\mu^-\mu^-$ events. The value of the fitted slope for the $p_\mu > 5$ GeV/c data in Fig. 1(c) is $(3.0\pm 1.3)\times 10^{-3}$ cm^{-1}, in agreement with the value $(4.0\pm 1.0)\times 10^{-3}$ cm^{-1} obtained from the calculated numbers[7] $N^{decay}(\mu^-\mu^-)$ shown in Table I. This agreement checks the validity of the decay

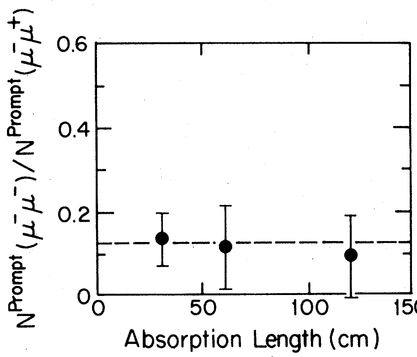

FIG. 2. Number of prompt $\mu^-\mu^-$ events relative to the number of prompt $\mu^-\mu^+$ events in each of the three targets for $p_\mu > 10$ GeV.

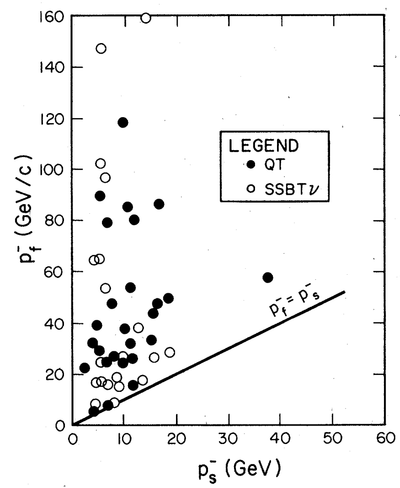

FIG. 3. Scatter plot of muon momenta for the $\mu^-\mu^-$ events.

in flight calculation and gives us confidence in using the calculated numbers $N^{\text{decay}}(\mu^-\mu^-)$ to determine the magnitude of the prompt $\mu^-\mu^-$ signal in each target for the $p_\mu > 10$ GeV/c data. We emphasize that a statistical test of the data of Figs. 1(c) and 1(d) can be made by assuming the intercept in Fig. 1(d) to be zero and simultaneously requiring the slope to be consistent with the slope exhibited by the $p_\mu > 5$ GeV/c data of Fig. 1(c). The confidence level for the absence of a prompt $\mu^-\mu^-$ signal in the $p_\mu > 10$ GeV/c data determined in that way is 1.5%. The ratios $N^{\text{prompt}}(\mu^-\mu^-)/N^{\text{prompt}}(\mu^-\mu^+)$ shown in Fig. 2 are seen to be systematically nonzero and independent of absorption length. Averaging over all three targets we obtain $N^{\text{prompt}}(\mu^-\mu^-)/N^{\text{prompt}}(\mu^-\mu^+) = 0.12 \pm 0.05$ for $p_\mu > 10$ GeV/c.

Using the dichromatic beam at CERN, M. Holder *et al.* reported the observation of 257 $\mu^-\mu^+$ events and 47 $\mu^-\mu^-$ events, with a minimum muon-momentum cutoff at 4.5 GeV/c.[8] The target-detector of their experiment is mainly iron with an average hadronic absorption length of 30 cm. The ratio $N^{\text{obs}}(\mu^-\mu^-)/N^{\text{prompt}}(\mu^-\mu^+)$ for $p_\mu > 5$ GeV/c may be obtained using the reported muon momentum spectrum and π, K-decay contributions to the $\mu^-\mu^+$ events,[8] and is 0.17 ± 0.03. The good agreement between the two experiments [Fig. 1(c)] supports our measurement in the iron target.

The two $\mu^+\mu^+$ events observed in the SSBT($\bar{\nu}$) run each have one very low-energy muon (<5 GeV/c). Pion and kaon decays are estimated to yield 4 ± 2 events. Hence the two observed $\mu^+\mu^+$ events are compatible with background. If a prompt $\mu^+\mu^+$ signal were to exist at the same relative rate as the $\mu^-\mu^-$ signal, we would expect to observe a total of seven events.

Some interesting properties of the $\mu^-\mu^-$ events are shown in Figs. 3 and 4. Figure 3 shows the scatter plot of the momentum of the fast μ^- vs the slow μ^-. A large momentum asymmetry between the two muons is observed, similar to that in the $\mu^-\mu^+$ data. The distribution in the azimuthal angle between the two muons[4] is shown in Figs. 4(a) and 4(b) for the $\mu^-\mu^-$ and $\mu^-\mu^+$ events. Both distributions peak at $\Delta\varphi = 180°$, suggestive of a hadronic origin for the second muon.

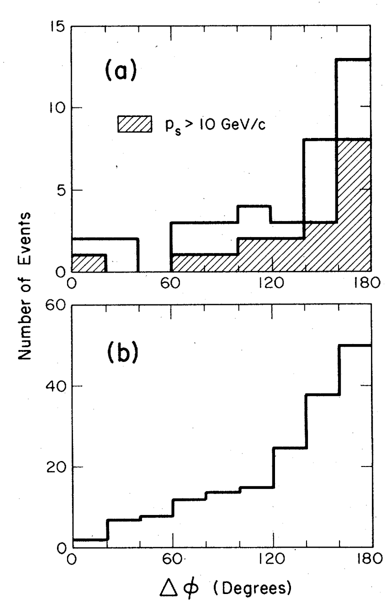

FIG. 4. Distributions of relative azimuthal angle between the two muons for the (a) $\mu^-\mu^-$ and (b) $\mu^-\mu^+$ events.

What are possible origins of prompt $\mu^-\mu^-$ events? Only $\mu^-\mu^+$ are expected if charmed particles are produced *singly* by neutrinos. Any mechanism to explain the $\mu^-\mu^-$ events that invokes new physics beyond charm[9] must be measured against the following alternatives: (a) radiative or direct muon-pair production in deep-inelastic charmed-current interactions,[10,11] (b) associated production of charmed particles.[12] However, $\mu^-\mu^-$ events could result from the mechanisms in (a) only if the μ^+ escapes experimental detection. Calculations[11] for mechanisms (a) lead to $R(\mu^-\mu^-)/R(\mu^-\mu^-\mu^+) < 1$, contrary to the experimental observation.[13] Therefore mechanism (a) is not likely to be the dominant source of like-sign dimuon events. Both $\mu^-\mu^-$ and $\mu^-\mu^-\mu^+$ are expected from associated charm production. The ratio $R(\mu^-\mu^-\mu^+)/R(\mu^-\mu^-)$ is expected to be roughly $B(C\to\mu+\nu+X)\simeq 0.1$, which is compatible with our observed ratio. The distributions shown in Figs. 3 and 4 are also consistent with this mechanism. However, the calculated rate for associated charm production may be too low.[12]

In conclusion, we have presented evidence for the production of prompt like-sign dimuons $(\mu^-\mu^-)$ by neutrinos. The rate of prompt $\mu^-\mu^-$ events relative to the prompt $\mu^-\mu^+$ events is measured to be 0.06 ± 0.05 for $p_\mu > 5$ GeV/c, and 0.12 ± 0.05 for $p_\mu > 10$ GeV/c. The properties of the $\mu^-\mu^-$ events are similar to those of the $\mu^-\mu^+$ events. We have no evidence for prompt $\mu^+\mu^+$ events produced by antineutrinos.

This work was supported in part by the U. S. Department of Energy and the National Science Foundation.

[(a)]Now at Istituto di Fisica, Università di Bologna, Bologna, Italy.

[(b)]On leave at the University of Pennsylvania from Istituto di Fisica dell'Università, Padova, Italy.

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[7]The 25% error of the pion- and kaon-decay calculation is determined by the error in the input to the calculation. This is due to the measurement errors of charged-hadron production in inelastic neutrino interactions and the uncertainties in the pion and kaon absorption processes.

[8]M. Holder *et al.*, Phys. Lett. 70B, 396 (1977).

[9]For example, the production and cascade decay of a new heavy lepton or new hadron with new quantum number.

[10]J. Smith and J. A. M. Vermaseren, State University of New York at Stony Brook Report No. ITP-SB-77-66 (unpublished); R. M. Barnett *et al.*, SLAC Report No. SLAC-PUB-2063, 1977 (unpublished).

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[13]In this experiment we obtain $R(\mu^-\mu^-)/R(\mu^-) = (4\pm 2)\times 10^{-4}$, averaged over E_ν (30–250 GeV) and over all targets. This is about 6 times the corresponding rate of trimuon events measured in this experiments.

Remarks on Single-Pion Production by the Weak Neutral Current

Evelyn H. Monsay
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439
(Received 24 May 1978)

I compare gauge-theory–model predictions for exclusive pion production by the weak neutral current, incorporating corrections for scattering off nuclear targets where appropriate, with all the available data. I find that, based on these data, no model should be completely ruled out.

Recently there has been much interest in extracting from data restrictions on the values of the neutral-current couplings of the u and d quarks. The restrictions imposed by neutrino elastic scattering have been investigated for various gauge-theory models by many authors.[1,2] Inclusive neutrino interactions have also been investigated,[3] and two sets of values for the neutral-current couplings, labeled A and B by Hung and Sakurai,[4] have been found to be consistent[2,4] with both the elastic and inclusive data. Values for the parameters of various gauge-theory models