Yield of prompt like-sign dimuons from neutrino interactions

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We present data on the production by neutrinos of a prompt $\mu^-\mu^-$ signal with a rate relative to the $\mu^-\mu^+$ rate (single charm production) of 0.07 ± 0.04, 0.12 ± 0.03, and 0.12 ± 0.03 for $p_\mu>5$, >10, and >15 GeV/c, respectively. The energy dependence of the ratio $N^{\rm pr}(\mu^-\mu^-)/N(\mu^-)$ is also presented. Like-sign dimuon data from various experiments are summarized and discussed. Our observed $\mu^-\mu^-$ rate is roughly two orders of magnitude larger than that expected from leading-order quantum-chromodynamic calculations of associated charm production.

Previously reported data[1] suggested the existence of a prompt like-sign negative-dimuon signal in inelastic neutrino interactions which was significantly larger in rate than the signal expected from known or anticipated sources, including leading-order quantum-chromodynamics (QCD) calculations of associated charm production.[2] In this paper we present stronger experimental evidence for the large rate of production of prompt like-sign dimuons, and show the energy dependence of the like-sign dimuon yield. We also summarize like-sign dimuon data from various experiments, and remark on certain noteworthy discrepancies.

The data were acquired at Fermilab using a quadrupole triplet (QT) beam with 400-GeV incident protons.[3] The observed average energy of the neutrino-induced charged-current (CC) events in that beam was 97 GeV. The detector for this experiment[4] shown in Fig. 1 consisted of three targets (for neutrino interactions) of different densities: an iron target (FeT), a liquid-scintillator calorimeter (LiqC), and an iron-plate calorimeter (FeC). A large-solid-angle muon spectrometer of iron toroidal magnets and optical spark chambers was located downstream of the last target (FeC) to measure the vector momentum of outgoing muons from neutrino interactions in the targets.

Dimuon-event candidates were selected by two complete scans of the optical-spark-chamber film. Based on the scanning information a cut was imposed to select candidates for which the momentum and charge of both muons could be accurately determined. Event candidates passing the scan cut were examined by a physicist using an interactive graphics terminal to associate the sparks in the various optical views with the appropriate muon track, and thereby to pass the event for momentum fitting and charge assignment or to reject it. The sample of fitted dimuon events within the fiducial volume was subjected to a second examination by physicists for goodness of track and vertex fits, relative timing, ionization of the two tracks, and charge assignment. The final event sample, reported here, consists of 158 $\mu^-\mu^-$ and 769 $\mu^-\mu^+$ events produced by neutrinos with a minimum-muon-momentum cutoff of 5 GeV/c. The average visible energy of the $\mu^-\mu^-$ events is 143 GeV, and of the $\mu^-\mu^+$ events is 136 GeV.

The antineutrino component of the QT beam also gave rise to samples of like-sign ($\mu^+\mu^+$) and opposite-sign ($\mu^+\mu^-$) events. Separation of neutrino-induced and antineutrino-induced opposite-sign dimuon events was based on the value of the transverse muon momentum $p_\perp$ relative to the incoming neutrino direction. (Events were designated as neutrino-induced if $[p_\perp(\mu^-)-p_\perp(\mu^+)]/[p_\perp(\mu^-)+p_\perp(\mu^+)]>-0.1$.) We have not attempted a detailed analysis of the $\mu^+\mu^+$ sample because it is statistically much less significant than the $\mu^-\mu^-$ sample. For $p_\mu>10$ GeV/c [where the ratio of the signal to

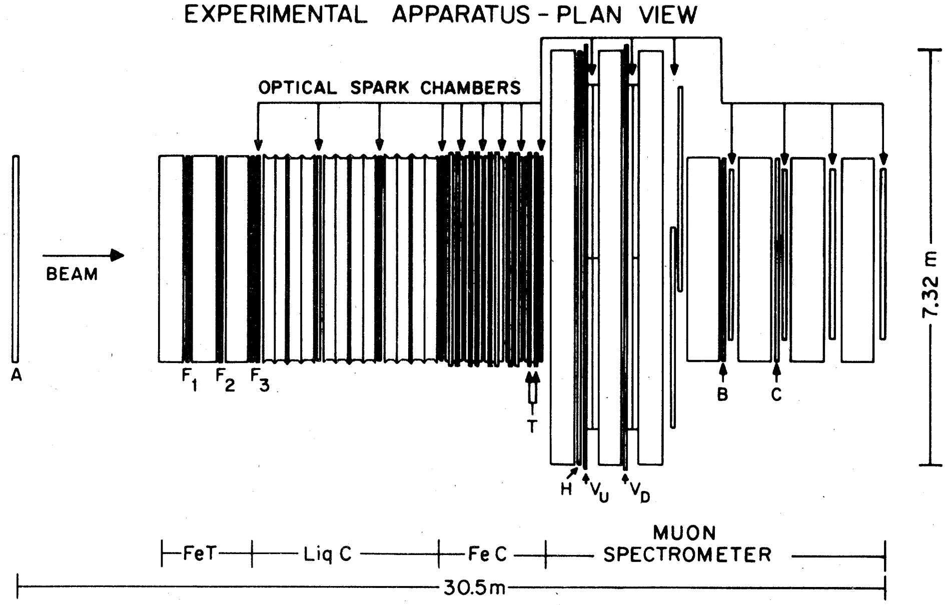

FIG. 1. Plan view of the experimental apparatus indicating the iron target (FeT), liquid calorimeter (LiqC), iron-plate calorimeter (FeC), trigger counters (A, F_1, F_2, F_3, T, H, V_U, V_D, B, C), spark-chamber positions, and the muon spectrometer. The fiducial masses for the three targets were 117 metric tons for the FeT (3.1 m× 3.1 m× 3.1 m), 30 metric tons for the LiqC (2.4 m× 2.4 m× 5.5 m), and 56 metric tons for the FeC (3.1 m× 3.1 m× 1.8 m).

the decay background (see below) is greater than unity], there are 11 $\mu^+\mu^+$ and 104 $\mu^+\mu^-$ events. The corresponding numbers of neutrino-induced events with $p_\mu > 10$ GeV/c are 81 $\mu^-\mu^-$ and 525 $\mu^-\mu^+$.

The data were corrected for geometric acceptance, triggering efficiency, and scanning and momentum-fitting efficiencies. The correction for geometric acceptance was carried out in a model-independent way. Each event was rotated about a line passing through the event vertex and parallel to the incident neutrino beam direction. In addition the vertex position of the event was varied in the transverse dimensions within the fiducial region. Then the ratio of the number of rotations in which both muons were accepted by the magnetic spectrometer to the total number of rotations specified the geometrical acceptance for the given event. The other corrections were determined empirically. The weighting factors representing these combined corrections, averaged over all $\mu^-\mu^+$ events with $p_\mu > 5$ GeV/c, were 1.9, 2.1, and 1.7 for the FeT, FeC, and LiqC, respectively; the corresponding factors for the $\mu^-\mu^-$ events were 2.2, 2.4, and 1.8. In the ratios of like-sign to opposite-sign dimuons the above corrections are applied but are seen to cancel to a reasonable approximation. The corrections are necessary to obtain dimuon-to-single-muon ratios.

Delineation of a prompt-dimuon rate relies crucially on knowledge of the magnitude of backgrounds resulting from decays in flight of pions and kaons produced in inelastic CC neutrino interactions. To determine this background we have made calculations which depend on measured properties of pion and kaon production from neutrino interactions[5] and pion- and kaon-nucleus interaction cross sections.[6]

The different effective hadron absorption lengths of the three target-detectors in this experiment (31 ± 3 cm for FeT, 61 ± 4 cm for FeC, and 120 ± 9 cm for LiqC, including end effects and finite target sizes) provided an independent check of the

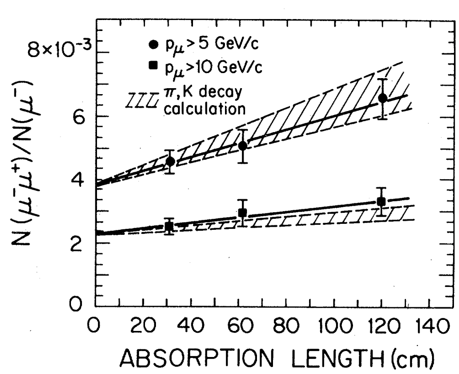

FIG. 2. Dependence of the ratio $N(\mu^-\mu^+)/N(\mu^-)$ on effective absorption length for the three targets. Solid lines are best fits to the data points. Shaded regions represent the uncertainty of the calculated backgrounds due to pion and kaon decays.

validity of the pion and kaon decay calculations. The observed slope of the linear dependence on absorption length of the $\mu^-\mu^+$ rate relative to the μ^- rate is a direct measurement of the hadron decay background in that channel. We have used the $\mu^-\mu^+$ sample for this purpose because (i) the higher rate in the $\mu^-\mu^+$ channel allows for better statistical accuracy, and (ii) the rate for the residual prompt $\mu^-\mu^+$ signal, most of which is due to single-charm production, is by now well known.[7] Figure 2 shows the measured ratio $N(\mu^-\mu^+)/N(\mu^-)$ as a function of absorption length for different cutoffs on the momentum of either muon. The solid lines in Fig. 2 are best fits to the $\mu^-\mu^+$ data and yield the intercepts $(0.39 \pm 0.05) \times 10^{-2}$ and $(0.23 \pm 0.03) \times 10^{-2}$ for $p_\mu > 5$ GeV/c and $p_\mu > 10$ GeV/c, respectively. These values are in good agreement with the measured rate for neutrino-induced charmed-particle production and decay[7] with $p_\mu > 5$ GeV/c, and the rate expected from a charm-model calculation with $p_\mu > 10$ GeV/c. The shaded regions in Fig. 2 are the sums of the measured prompt signals (the intercepts above) and the predicted pion and kaon background with a spread of ±25% due to uncertainties in the input data to the decay calculation. We note that the agreements on the slope between the data and the calculation are good for both the $p_\mu > 5$ GeV/c and $p_\mu > 10$ GeV/c samples, and conclude that the decay calculation

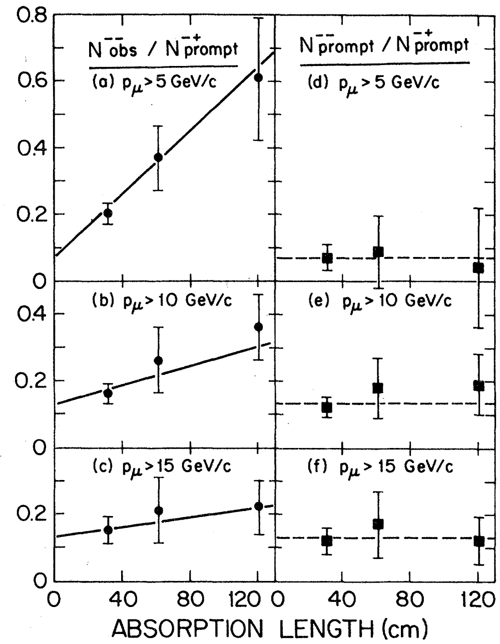

FIG. 3. (a)–(c) Ratio of $N^{\text{obs}}(\mu^-\mu^-)/N^{\text{pr}}(\mu^-\mu^+)$ as a function of absorption length. The solid lines are fits to the data with the slope fixed by the decay calculation. (d)–(f) Ratio of $N^{\text{pr}}(\mu^-\mu^-)/N^{\text{pr}}(\mu^-\mu^+)$ as a function of absorption length. The errors on the points include the uncertainty in the background calculation. The dashed line represents the weighted average.

TABLE I. Summary of the $\mu^-\mu^-$ and $\mu^-\mu^+$ data from the FeT of this experiment. No correction has been made for trimuon events that might leak into the dimuon sample because less than 2% of the $\mu^-\mu^-$ sample with $p_\mu > 5$ GeV/c is due to such leakage. The appearance of a smaller number of prompt $\mu^-\mu^-$ events at $p_\mu > 5$ GeV/c than at $p_\mu > 10$ GeV/c is due primarily to the larger decay background subtraction at the lower momentum cutoff which is reflected in the large error on the entry for $p_\mu > 5$ GeV/c. Possible systematic effects may also contribute to the uncertainty in the number of events at $p_\mu > 5$ GeV/c since our studies show that a small error in the calibration of the muon spectrometer or in the muon detection efficiency would have a significant effect at the lower momentum cutoff but a minor effect at the higher momentum cutoffs. The ratio of like-sign to opposite-sign events is largely independent of such systematic effects.

p_μ cutoff (GeV/c)		5	10	15
$N(\mu^-\mu^-)$	(Raw)	(68 ± 8)	(44 ± 7)	(24 ± 5)
	Corrected	149 ± 20	85 ± 14	44 ± 11
	π/K decay	97 ± 24	20 ± 5	7 ± 2
	Prompt	52 ± 31	65 ± 15	37 ± 11
$N(\mu^-\mu^+)$	(Raw)	(471 ± 22)	(359 ± 19)	(211 ± 15)
	Corrected	883 ± 43	555 ± 29	313 ± 22
	π/K decay	145 ± 36	33 ± 8	12 ± 3
	Prompt	738 ± 56	522 ± 30	301 ± 22
$N^{\text{pr}}(\mu^-\mu^-)/N^{\text{pr}}(\mu^-\mu^+)$		0.07 ± 0.04	0.12 ± 0.03	0.12 ± 0.04
$10^2[N^{\text{pr}}(\mu^-\mu^+)/N(\mu^-)]$		0.39 ± 0.05	0.27 ± 0.03	0.16 ± 0.02
$10^3[N^{\text{pr}}(\mu^-\mu^-)/N(\mu^-)]$		0.27 ± 0.17	0.34 ± 0.09	0.19 ± 0.06
$N(\mu^-)$ (calculated without a p_μ cutoff)			$(1.9 \pm 0.2) \times 10^5$	

is indeed reliable to the stated accuracy.

Figures 3(a)–3(c) show the ratios of observed $\mu^-\mu^-$ events (N^{obs}) to prompt $\mu^-\mu^+$ events (N^{pr}), plotted against absorption length. The number of prompt $\mu^-\mu^+$ events at a given muon-momentum cutoff is obtained by subtracting the calculated pion and kaon decay background from the total of observed $\mu^-\mu^+$ events. The straight lines shown are one parameter fits to the data points *with the slopes fixed by the same background calculation as above* applied to the production and decay of negative hadrons. We emphasize that (i) the data are in good agreement with the slopes obtained from the calculation, and (ii) the intercepts resulting from the fits are systematically nonzero and positive in all three cases. Furthermore, given the calculated slope the probability that all of the $\mu^-\mu^-$ events with, e.g., $p_\mu > 10$ GeV/c result from pion and kaon background is less than 10^{-4} (χ^2 of 28 for 2 degrees of freedom).

The ratios $N^{pr}(\mu^-\mu^-)/N^{pr}(\mu^-\mu^+)$ are shown in Figs. 3(d)–3(f). The ratios are independent of absorption length and are systematically positive. Using all three targets, we obtain $N^{pr}(\mu^-\mu^-)/N^{pr}(\mu^-\mu^+) = 0.07 \pm 0.04$ for $p_\mu > 5$ GeV/c, and 0.12 ± 0.03 for $p_\mu > 10$ and 15 GeV/c. In Table I is presented a summary of the $\mu^-\mu^-$ and $\mu^-\mu^+$ data from the FeT (for which the signal-to-background ratio is best) for the momentum cutoffs 5, 10, and 15 GeV/c.

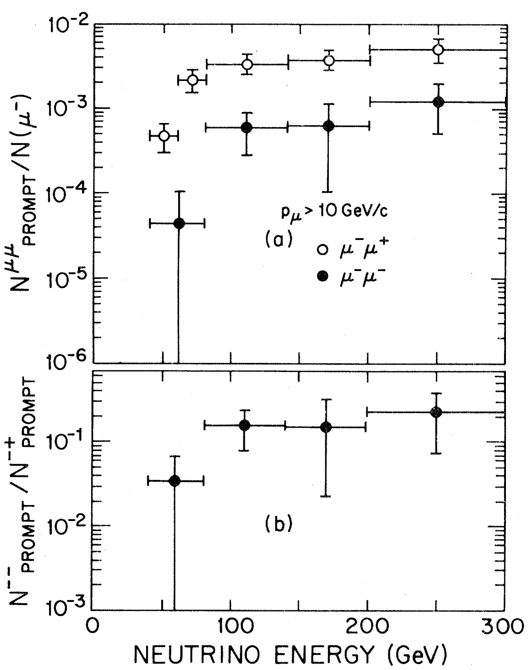

FIG. 4. (a) Rate of prompt dimuons relative to all charged-current neutrino interactions as a function of neutrino energy for both the opposite- and like-sign events with $p_\mu > 10$ GeV/c. (b) Ratio of prompt like-sign to prompt opposite-sign yield ($p_\mu > 10$ GeV/c) versus neutrino energy.

We show in Fig. 4(a) the $\mu^-\mu^-$ production per CC neutrino interaction as a function of neutrino energy for the $p_\mu > 10$ GeV/c data from the LiqC and FeC (in which the subtracted hadron decay background is about 40% of the observed $\mu^-\mu^-$ signal). For comparison the $\mu^-\mu^+$ production for $p_\mu > 10$ GeV/c is also displayed. The ratio of $\mu^-\mu^-$ yield to $\mu^-\mu^+$ yield as a function of energy is shown in Fig. 4(b).

The relative rates presented here are compared with those from previous experiments on like-sign dimuons[1] in Table II, where the agreement between the results of this experiment and those of Holder *et al.*[8] and Benvenuti *et al.*[9] is seen to be good. However, there is disagreement with the results of de Groot *et al.*[10] There are two aspects to this disagreement. (i) Although the ratio $N^{pr}(\mu^-\mu^-)/N^{pr}(\mu^-\mu^+)$ is the same within errors for the four experiments (with $p_\mu > 4.5$, 5, 6.5 GeV/c), the value of $N^{pr}(\mu^-\mu^-)/N(\mu^-)$ of de Groot *et al.* is about an order of magnitude smaller than the average of the other experiments. The value of $N^{pr}(\mu^-\mu^+)/N(\mu^-)$ for de Groot *et al.* in column 6 is obtained directly from the ratios in columns 4 and 5, and is seen to be significantly smaller than the other values in column 6. It has been stated[11] that this discrepancy is due to the different cuts and neutrino spectrum employed by de Groot *et al.* Accordingly, we have used the measured dependence of $N^{pr}(\mu^-\mu^+)/N(\mu^-)$ on neutrino energy for $p_\mu > 5$ GeV/c and $p_\mu > 10$ GeV/c [see, e.g., Fig. 4(a) and data from Ref. 7] to explore the effect on the integrated charm yield of the different muon-momentum cutoffs and different neutrino spectra in the experiments listed in Table II. We are unable to account for the discrepancy in $N(\mu^-\mu^+)/N(\mu^-)$, i.e., in charm yield, between de Groot *et al.* and the other experiments by either means.[12] (ii) In addition, the values in Table II of the directly observed ratio $N^{pr}(\mu^-\mu^-)/N^{pr}(\mu^-\mu^+)$ at $p_\mu > 10$ GeV/c are in serious diagreement. We emphasize that, using our decay-background calculation, we predict values of the decay background at $p_\mu > 6.5$ GeV/c and $p_\mu > 10$ GeV/c which are in agreement with the values used by de Groot *et al.* within 15%. Hence the disagreement in $N^{pr}(\mu^-\mu^-)/N^{pr}(\mu^-\mu^+)$ at $p_\mu > 10$ GeV/c is not due to a disagreement on the decay background that is subtracted from the observed dimuon samples of the two experiments.

Finally, we note that the distributions in event energy, transverse and longitudinal muon momenta, Bjorken x and y, etc., of $\mu^-\mu^-$ events with $p_\mu > 10$ GeV/c are all consistent with those for CC neutrino events in which a second muon emerges from the decay of a hadron at the hadron vertex.

TABLE II. Summary of world data on like-sign dimuon yields. NBB denotes narrow-band beam; WBB denotes wide-band beam.

References	Beam	Cuts [a] $p_\mu >$ (GeV/c)	$\frac{N^{pr}(\mu^-\mu^-)}{N^{pr}(\mu^-\mu^+)}$	$\frac{10^4 N^{pr}(\mu^-\mu^-)}{N(\mu^-)}$	$\frac{10^2 N^{pr}(\mu^-\mu^+)}{N(\mu^-)}$
Holder *et al.* (Ref. 8)	NBB (200 GeV π/K)	4.5	0.05 ± 0.03	3 ± 2	0.42 ± 0.04 [b]
Benvenuti *et al.* (Ref. 9)	WBB (QT) (400 GeV)	5	0.06 ± 0.05	2.4 ± 2.0	0.40 ± 0.10
		10	0.12 ± 0.05		
de Groot *et al.* (Ref. 10)	WBB (horn) (350 GeV)	6.5	0.041 ± 0.022	0.34 ± 0.18	0.083 ± 0.007 [c]
		10	0.020 ± 0.013		
This experiment	WBB (QT) (400 GeV)	5	0.07 ± 0.04	2.7 ± 1.6	0.39 ± 0.05
		10	0.12 ± 0.03	3.0 ± 0.8	0.23 ± 0.03

[a] $E_\nu > 30$ GeV all cases.
[b] Derived from the data in M. Holder *et al.*, Ref. 7.
[c] Derived from columns 4 and 5.

These distributions as well as those for $\mu^-\mu^+$ events will be discussed in a later publication.

To summarize, we have presented evidence for the production of prompt $\mu^-\mu^-$ events in high-energy neutrino interactions which confirms and strengthens our earlier observation of a large yield of like-sign dimuons relative to opposite-sign (charm) dimuons. Our observed yield of prompt $\mu^-\mu^-$ events is roughly two orders of magnitude larger than the prediction for associated charmed-particle production given by leading-order QCD calculations, which suggests that additional thought be given to other possible origins of like-sign dimuons.

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[12]We find the dependence of the charm rate (integrated over energy) on different neutrino spectra and different muon-momentum cutoffs to be as follows. Using the 350-GeV horn neutrino spectrum of de Groot *et al.* and the measured energy dependence of the $\mu^-\mu^+/\mu^-$ yield [Ref. 7 and Fig. 4(a) of this paper], we obtain $N^{pr}(\mu^-\mu^+)/N(\mu^-) \approx 0.30\times 10^{-2}$ for $p_\mu > 5$ GeV/c and $E_\nu > 30$ GeV, and $N^{pr}(\mu^-\mu^+)/N(\mu^-) = 0.16\times 10^{-2}$ for $p_\mu > 10$ GeV/c and $E_\nu > 30$ GeV. Corresponding values for our QT beam are 0.39×10^{-2} and 0.23×10^{-2}. No explanation is given by de Groot *et al.* for the difference between the values of $N^{pr}(\mu^-\mu^+)/N(\mu^-)$ in Holder *et al.* and in de Groot *et al.*, even though both experiments were done by the same experimenters.