Neutrino Production of Same-Sign Dimuons

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In a sample of 670000 charged-current neutrino events, 101 $\mu^-\mu^-$ events have been observed, with 30 GeV $< E_\nu <$ 600 GeV and $P_\mu > 9$ GeV/c for both muons. After background subtraction, 18.5 ± 13.9 events remain, yielding a prompt rate of $(5.5 \pm 4.1) \times 10^{-5}$ per charged-current event. A sample of 124000 antineutrino events yields 15 $\mu^+\mu^+$ events, giving 6.4 ± 4.2 events after background subtraction and a prompt rate of $(1.0 \pm 0.7) \times 10^{-4}$ per charged-current event. The numbers and kinematic distributions of these events are consistent with standard-model sources.

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We report results of an experiment studying neutrino- and antineutrino-induced interactions with nucleons, producing two muons of the same electric charge. Such events are known to occur from hadron decay in the hadron showers of charged-current events; however, several previous experiments[1-3] performed at neutrino energies less than 300 GeV have observed rates higher than expected from that source. The observed excess, puzzling in the context of the standard model, exhibited a strong increase with energy. This high-statistics experiment, which is the first measurement of same-sign dimuon production above 300 GeV, provides new data addressing this issue.

The experiment was performed in the Fermilab Tevatron quadrupole-triplet wide-band neutrino beam. The detector[4] consists of a target calorimeter instrumented with liquid scintillation counters and drift chambers followed by an iron toroidal muon spectrometer. The 690-ton target calorimeter, $3 \times 3 \times 18$ m^3, is constructed of 168 5-cm-thick steel plates, 84 liquid scintillation counters (located every 10 cm of steel), and 42 drift chambers (located every 20 cm of steel), each with two orthogonal planes. These chambers and counters, instrumented with time-digitizing electronics, determine the event time to within 5 ns. The average density of the calorimeter is 4.20 g/cm^3. The rms hadron energy resolution is $(0.89\ \text{GeV}^{1/2})\sqrt{E}$.

The muon spectrometer consists of three toroidal magnets with a 1.8-m outer radius and a 1.27-cm-radius hole for the coils. Each toroid contains eight 20-cm magnetized steel segments interspersed with drift chambers and acrylic scintillation counters. A group of five 3×3-m^2 drift chambers is located immediately downstream of each toroid as well as 3 and 7 m downstream of the last toroid. The total transverse momentum kick of the muon spectrometer is 2.4 GeV/c and the fractional rms momentum resolution is 11%.

To ensure hadron shower containment and good resolution, events were required to have a transverse vertex within a 2.5×2.5-m^2 square and a circle of 1.5-m radius, both of which were centered on the longitudinal axis of the apparatus. Events were also required to have a longitudinal vertex at least 4.4 m (2.0 m of iron) upstream of the downstream end of the target in order to avoid leakage of the hadron shower into the muon spectrometer. To ensure proper reconstruction of the muon, the track segments immediately in front of and behind the first toroid were required to be at least 10 cm inside the toroid's outer edge, and to be outside a 15-cm radius from the toroid center for at least 70% of their length. The track was also required to intersect a triggering hodoscope located after the first toroid.

Each reconstructed muon track was required to have $E_\mu > 3$ GeV at its entry into the first toroid and $E_\mu > 9$ GeV at the event vertex. The time of the track, as found by the groups of drift chambers following each toroid, was required to be within 36 ns of the time obtained from the calorimeter counters and toroid hodoscope. The charged-current event sample passing these cuts includes 670000 ν_μ- and 124000 $\bar{\nu}_\mu$-induced events.

A computer search for multimuon events used the independent criteria of excess calorimeter counter pulse height downstream of the end of the hadron shower or indications of two tracks in the calorimeter drift chambers. The resulting selection of 6300 multimuon candidates (before cuts) had a measured efficiency exceeding 99.5%. All candidates were double scanned by physicists for errors in track reconstruction which were corrected interactively.

The events in the final multimuon sample were required to have two muon tracks passing the above cuts, with a transverse separation $\Delta s < 15$ cm at the point of the closest approach, and a time difference $\Delta t < 28$ ns as measured by fits to tracks in the toroid gaps. These cuts reduced the background caused by accidental temporal and spatial overlays of charged-current events to 0.4 ± 0.2 $\mu^-\mu^-$ and 0.02 ± 0.01 $\mu^+\mu^+$ events.

The multimuon sample contained 1997 events passing all cuts. Of these, 68 were determined to be trimuons from a third track which penetrated more than 2 m of steel, corresponding to a minimum muon energy of 3.1 GeV. The remaining 1929 dimuon events comprised 1813 opposite-sign dimuons and 116 same-sign dimuons; of the latter 101 were classified ν_μ induced ($\mu^-\mu^-$) and 15 were classified $\bar{\nu}_\mu$ induced ($\mu^+\mu^+$).

The two principal background sources of same-sign dimuons are muonic decays of primary hadrons produced at the hadron vertex in a charged-current event (vertex background) and the muonic decays of hadrons produced in secondary interactions in the hadron shower (shower background).

The vertex background was calculated from the inclusive primary hadron spectra obtained for lepton-nucleon interactions in the Lund Monte Carlo program.[5] The program was used with its default parameters except for two modifications: The minimum energy $E_{\rm min}$ for quark-antiquark pair creation was set equal to 0.2 GeV instead of 1.1 GeV, and the strangeness-suppression parameter λ was set equal to 0.2 instead of 0.3. With these modifications, the program provides a good description of fragmentation measurements from νN[6,7] and μp[8] scattering data.

For ν_μ-induced events, the largest systematic error in the vertex background (7.5%) is due to experimental uncertainties in the fragmentation functions used to set the Lund parameters. This includes the uncertainty in the extrapolation of Lund fragmentation up to W^2 (the squared invariant mass of the hadronic system) of 500 GeV^2/c^4, which is beyond the range available from νN fragmentation data (200 GeV^2/c^4). The systematic error due to uncertainty in the ratio of pions to charged hadrons is 2%, and that due to uncertainty in the K/π ratio is 5% (studied by the variation of λ from 0.1 to 0.3, which brackets the νN and μp results). Changing from $E_{\rm min}$ to 1.1 GeV leaves the vertex background unchanged to 1%. On the basis of ν_μ studies with H and Ne targets[6] and muon studies on C and Cu targets,[8] we estimate the uncertainty from the use of νNe fragmentation data for an iron target to be 5%. Finally, there are small (2%) systematic errors due to uncertainties in the interaction lengths of hadrons and parametrizations of Lund fragmentation used in our calculation. The total systematic error in the vertex component from combining all the individual errors in quadrature is 11% for ν_μ and, from similar studies, 18.5% for $\bar{\nu}_\mu$.

The subsequent interactions of the primary hadrons produce the shower component of the hadron decay background. Muon production from this source, including a small (~10%) contribution from hadronic charm production, has been measured with beams of 50-, 100-, and 200-GeV hadrons interacting in the Lab E calorimeter. A hadron shower simulation extended the muon-production data over the full range of hadron energies and muon momenta. This simulation made use of πC fragmentation data,[9] and a hadronic nuclear reweighting scheme[10] to incorporate nuclear effects into the hadron Lund Monte Carlo program.[5] The 15% uncertainty in the muon-production measurements combined with the uncertainty in the input spectrum of vertex hadrons yields an overall systematic error on the ν_μ shower component of 18.5% (24% for $\bar{\nu}_\mu$).

The total $\mu^-\mu^-$ hadron decay background is 76.9

TABLE I. The energy dependence of the ν_μ-induced single-muon data, $\mu^-\mu^-$ data, total background, background-subtracted data, and the acceptance-corrected ratio of background-subtracted $\mu^-\mu^-$ data to single-muon events.

Energy (GeV)	Data ($10^3\,\mu^-$)	Data $\mu^-\mu^-$	Bkg. $\mu^-\mu^-$	Data − Bkg. $\mu^-\mu^-$	Data − Bkg. $\mu^-\mu^-/\mu^-$ (10^{-4})
30–100	239	7	6.9 ± 0.8	0.1 ± 2.8	0.01 ± 0.33
100–200	213	17	22.9 ± 2.6	-5.9 ± 4.9	-0.67 ± 0.55
200–300	150	44	30.9 ± 3.7	13.1 ± 7.6	1.9 ± 1.1
300–400	50	24	14.8 ± 2.0	9.2 ± 5.3	3.7 ± 2.1
400–500	14	9	5.4 ± 0.8	3.6 ± 3.1	5.1 ± 4.5
500–600	4	0	1.4 ± 0.3	-1.4 ± 1.1	-9.7 ± 7.4
Total	670	101	82.5 ± 9.7	18.5 ± 13.9	0.55 ± 0.41

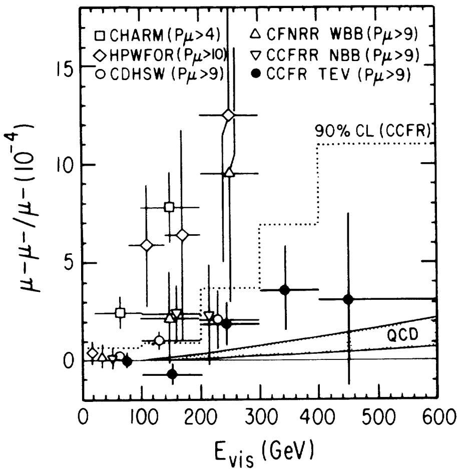

FIG. 1. The rates for prompt $\mu^-\mu^-$ production relative to single-muon charged-current events for the experiments listed in the text. The CCFR TEV points and the dotted line representing the 90%-C.L. upper limit are from this experiment. The shaded band represents the QCD calculation referenced in the text. CHARM, Ref. 1; HPWFOR, Ref. 2; CDHSW, Ref. 15; CFNRR, Ref. 3; CCFRR, Ref. 14.

± 9.4 events; of these 26.7 are shower events and 50.2 are vertex events. For $\mu^+\mu^+$ the total decay background is 7.9 ± 1.5 events.

The final source of background is trimuon events in which the unlike-sign muon traverses less than 2 m of steel and is hidden by the hadron shower. Trimuon production was modeled with use of the measured spectrum of hadronically produced muon pairs from experiments on $\pi + \text{Be} \rightarrow \mu^+\mu^- + X$.[11] The level and spectrum of a smaller component due to radiative muon pair production was based on theoretical calculations.[12] The sum of these two processes was normalized to the 68 observed trimuons. The misidentified trimuon background was 5.0 ± 2.0 events for $\mu^-\mu^-$ and 0.5 ± 0.2 events for $\mu^+\mu^+$.

The 101 $\mu^-\mu^-$ events have a total background from overlays, trimuons, and hadron decay of 82.5 ± 9.7 events, while the fifteen $\mu^+\mu^+$ events have a total background of 8.6 ± 1.6 events. This yields an observed prompt excess of 18.5 ± 13.9 $\mu^-\mu^-$ and 6.4 ± 4.2 $\mu^+\mu^+$ events. After correction for acceptance, with the model of the decay background, the averaged ratio of excess same-sign dimuon events to single-muon events with $P_\mu > 9$ GeV/c is $(5.5 \pm 4.1) \times 10^{-5}$ for $\langle E_\nu \rangle = 160$ GeV, and $(1.0 \pm 0.7) \times 10^{-4}$ for $\langle E_{\bar{\nu}} \rangle = 120$ GeV. At 90% confidence level (C.L.), these ratios are less than 1.16×10^{-4} and 2.16×10^{-4}, respectively.

The energy dependence of the ν_μ events and rates is shown in Table I. Our rate for $E_\nu < 100$ GeV is consistent with the limit of 8×10^{-5} on dilepton production ($P_\mu > 5$ GeV/c, $P_e > 4$ GeV/c) found in ν-Ne interactions.[13] Figure 1 shows the energy dependence of the

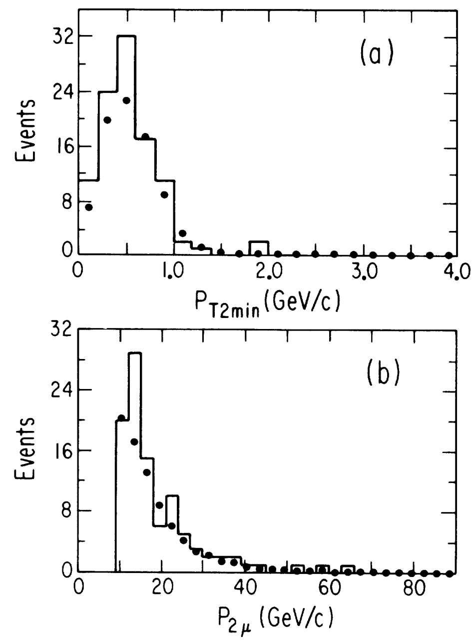

FIG. 2. Distributions of $\mu^-\mu^-$ data (histogram) and background (dots) for (a) the chosen second muon's momentum component perpendicular to the axis of the hadron shower and (b) its total momentum.

prompt $\mu^-\mu^-/\mu^-$ ratio for this experiment and the measurements of Lang *et al.*,[14] Burkhardt *et al.*,[15] Jonker *et al.*,[1] Trinko *et al.*,[2] and Nishikawa *et al.*[3] Our rates lie below those of other experiments and do not exhibit a strong energy dependence.

Possible prompt sources of $\mu^-\mu^-$ from neutrinos are perturbative QCD processes such as the production, by gluon bremsstrahlung, of a charm-anticharm quark pair ($c\bar{c}$) with $\bar{c} \rightarrow \mu^- + \bar{\nu}_\mu + X$. Figure 1 shows the range of predicted rates from a $c\bar{c}$ bremsstrahlung calculation,[16] contributing less than five events for this experiment. The major uncertainties in this calculation are due to assumptions regarding the charm-quark mass, fragmentation, and the scales of the structure functions and running coupling constant. The 90%-C.L. limits from these data are consistent with the full range of theoretical predictions for this process.

A $\mu^-\mu^-$ signal might result from reactions that create a charmed quark (ordinarily giving a $\mu^-\mu^+$ event) where the charmed-quark fragments to a D^0 meson that oscillates into a $\bar{D}^0$ before decay. From the measured relative fractions of D^0, D^+, and Λ_c^+ produced by ν_μ interactions in an emulsion experiment[17] and the measured semileptonic branching ratios of these particles,[18] we estimate that (30 ± 10)% of the charm $\mu^-\mu^+$ signal is due to D^0 decay. Using this information and a previous measurement of $\nu_\mu N$ charm production,[14] we calculate that 1% D^0-$\bar{D}^0$ mixing would result in 5 ± 2 $\mu^-\mu^-$ events. Therefore, the observed prompt excess of

18.5 ± 13.9 $\mu^-\mu^-$ events sets a 90%-C.L. upper limit of 9% on D^0-$\bar{D}^0$ mixing, which is larger than existing limits.[18,19]

The distributions of kinematic quantities of the observed $\mu^-\mu^-$ events can be compared with those expected from the background. We define the second muon to be that which has a smaller momentum component perpendicular to the axis of the hadron shower ($P_{T2\min}$). This axis is determined from the total measured event energy, the ν_μ-beam direction, and the measured vector momentum of the chosen first muon. Figure 2(a) shows the $P_{T2\min}$ distribution for the 101 $\mu^-\mu^-$ data (histogram) and 82.5 background events (dots). Figure 2(b) shows the distribution in total momentum for the second muon defined above. The shapes of these kinematic distributions for the dimuon data are similar to those for the background.

The observed number of same-sign dimuons above background is consistent with the hypothesis of no prompt signal. At energies less than 300 GeV, our prompt $\mu^-\mu^-/\mu^-$ rate of $(2.4 \pm 3.8) \times 10^{-5}$ for $\langle E_\nu \rangle = 135$ GeV is lower than other experiments, and less than 8.3×10^{-5} at 90% C.L. We also have the first measurement of the prompt rate above 300 GeV: $(3.4 \pm 1.9) \times 10^{-4}$ for $\langle E_\nu \rangle = 370$ GeV ($< 6.3 \times 10^{-4}$ at 90% C.L.). At these higher energies, the small excess of $\mu^-\mu^-$ events over background is consistent with, but does not require, such perturbative QCD processes as $c\bar{c}$ gluon bremsstrahlung. The kinematic distributions are consistent with the expected background. In this unique high-statistics sample, we do not observe a level of same-sign dimuon production between 30 and 600 GeV that requires an explanation outside the standard model.

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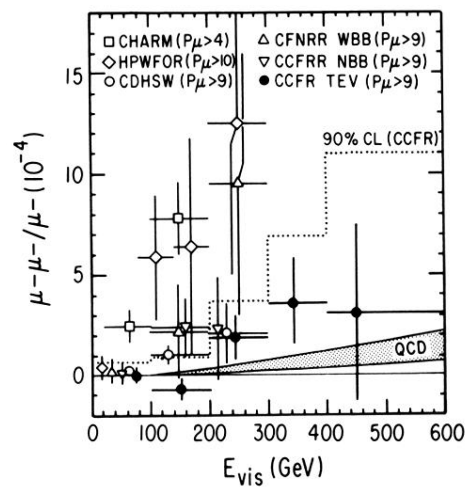

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