# Observation of Prompt Like-Sign Dimuon Production in Neutrino Reactions

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We report on the observation of twelve like-sign ($\mu^-\mu^-$) neutrino-induced dimuon events with muon momenta greater than 9 GeV. The background from $\pi$ and $K$ decay is 1.3 events so that we conclude that this prompt signal is real with a significance greater than 1 in $10^7$. Although the overall rate is higher than present theoretical estimates, the kinematic distributions of these events are qualitatively consistent with a picture of charm-anticharm production. The ratio of $\mu^-\mu^-/\mu^-$ shows a strong energy dependence and rises to $(2.5\pm1.0)\times10^{-3}$ at $E_\nu=250$ GeV.

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A unique tool to investigate new flavor production by the weak interactions has been multimuon production by neutrinos and antineutrinos. For example, the large rate for opposite-sign dimuon events and the increase of this rate with energy above 10 GeV was the first indication of a new heavy quark, charm.[1] Like-sign dimuon events, on the other hand, may be very significant and have been observed,[2-4] but are less well established experimentally because of large and uncertain backgrounds. This experiment establishes the existence of prompt like-sign dimuon events from neutrino interactions. The background is substantially lower than previous measurements[2-4] because of the high density of the detector, the higher neutrino-energy spectrum, and the kinematic restrictions on the observed muons. For like-sign dimuon events, the second $\mu^-$ cannot come from the decay of any known singly produced quark (i.e., $u$, $c$, $\bar{d}$, $\bar{s}$, or $\bar{b}$). Some calculations of like-sign dimuon events have been made with use of heavy leptons,[5] associated charm-anticharm production,[6,7] or cascades in which the second muon comes from second-generation decays of charm quarks. These calculations predict small cross sections with large energy dependences due to threshold effects.

We report here a measurement of like-sign dimuon production by neutrinos at energies up to 300 GeV. The experiment was performed at Fermilab with use of the quadrupole triplet beam with 400-GeV incident protons. The detector consisted of a dual-density steel target (160 tons), a steel hadron absorber (224 tons), and magnetized solid steel toroids (440 tons) for muon momentum analysis. The target was composed of eight 1.5 m× 1.5 m× 10 cm-thick steel plates interspersed with liquid scintillation counters. It was arranged in two densities (differing by a factor of 2) to check our empirical estimate of nonprompt sources of multimuon production at low muon energy. A spark chamber was placed every 20 cm of steel (40 cm of steel) for the low- (high-) density target to allow tracking of the muons from neutrino interactions. The low-density target was larger in the transverse dimension (1.5× 3

 

$m^2$) for hadron shower containment. The target was followed by a hadron absorber consisting of 28 3 m$\times$ 3 m$\times$ 10 cm-thick steel plates interspersed with scintillation counters every 10 cm of steel and spark chambers every 20 cm of steel. The 1.8-m-radius toroids, located directly downstream of the hadron absorber, imparted a 2.4-GeV transverse-momentum bend to the muons traversing them. The toroids were longitudinally segmented every 20 cm and instrumented with scintillation counters. Spark chambers every 80 cm were used to track the muon through the spectrometer. The hadron energy ($E_h$) was determined with a fractional accuracy of $1.1/\sqrt{E}$ (GeV) and the muon momentum measured to 10%.

The trigger requirements were that (1) no charged particle enter the front of the detector, (2) two counters in the target have more than minimum-ionizing pulse height, (3) a penetrating muon be present in the toroids, and (4) a minimum hadron energy of 7 GeV be deposited. For the investigation of like-sign ($\mu^-\mu^-$) events we also required that both muons have momenta greater than 9 GeV ($p_\mu^{\min}$) to reduce $\pi$- and $K$-decay nonprompt background. The fiducial volume includes events produced up to 12 cm from the target edges. A small correction (less than 10%) was applied to the hadron energy for events near the target edges to correct for the nonsampled hadron energy. All events with two muons were visually scanned to check for reconstruction errors. With an 82-ton fiducial volume and the requirement of a 9-GeV negative muon there remain 19 036 (17 203) 1 $\mu^-$ events, 47 (45) $\mu^-\mu^+$ events,[8] and 5 (7) $\mu^-\mu^-$ events in the high- (low-) density target. No $\mu^+\mu^+$ events were observed. Figure 1 shows the energy dependence of the $1\mu$ and $2\mu$ samples.

The use of the dual-density target in separating the prompt and nonprompt sources of opposite-sign dimuon events with $p_\mu^{\min}$ requirements lower than 9 GeV has been reported elsewhere.[9] The measured nonprompt rate reported there agrees with the calculated rate within 15%. In the present $\mu^-\mu^-$ sample the statistics are not adequate to separate the prompt and nonprompt contributions by a comparison of rates in the two different density targets. Rather we rely on the same calculation of the expected $\pi$- and $K$-decay background that uses experimental data on the hadronic production of muons in steel. The calculation uses a Field-Feynman quark-jet simulation program[10] which is based on fits to neutrino-induced hadron final-state data as measured in neon bubble-chamber experiments. This program provides

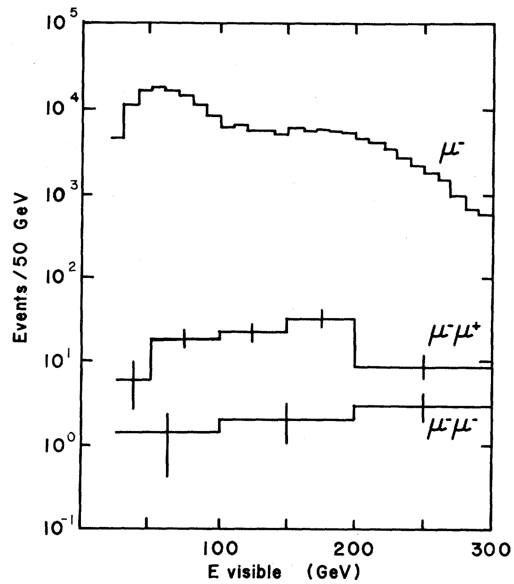


FIG. 1. Observed visible-energy distribution for the $\mu^-$, $\mu^-\mu^+$, and $\mu^-\mu^-$ samples with $p_\mu^{\min} = 9$ GeV.

the multiplicity and energy distributions for hadrons produced in the primary neutrino interactions. These distributions are then used as input to find the probability for first-generation pions and kaons to decay before interacting. The $\mu$-decay rate from subsequent interactions of these hadrons is determined with use of direct measurements of $\pi$-Fe interactions from an experiment[11] where both the prompt- and nonprompt-muon rates have been measured at several incident hadron energies. This method thus uses empirical data, except for first-generation decay, where it is assumed that $\nu$-Ne distributions are the same as the $\nu$-Fe distributions. At high hadron energies where the bubble-chamber data are relatively poor statistically the Field-Feynmann parametrization is assumed to be correct. This assumption has been cross checked with use of new bubble-chamber data[12] at higher energies directly instead of the Field-Feynman program results. The backgrounds estimated by either of these two methods agree to better than 0.3 events. Geometrical acceptance for the background is calculated under the assumption that the decay-muon direction is the same as the initial hadron-shower direction plus a perpendicular momentum typical of pion decay.

Background from trimuon events, where a muon is not identified, is negligible. With the $p_\mu^{\min}$ requirement reduced to 3.0 GeV, we observe three $3\mu$ events which correspond to a $3\mu/1\mu$ ratio

TABLE I. Data corrected for azimuthal acceptance and requiring $p_\mu^{\min} \geq 9$ GeV. $1\mu$ sample also requires $E_h \geq 9$ GeV. Note that the effect of $p_\mu^{\min}$ may be different for $\mu^-\mu^-$ and $\mu^-\mu^+$ (see text).

| Energy \ Events | $1\mu$ | $\mu^-\mu^+$ | $\mu^-\mu^-$ | $\mu^-\mu^-$ decay |
|---|---|---|---|---|
| 20–100 GeV | 9809 | 22.8 | 2 | 0.2 |
| 100–200 GeV | 6180 | 59.9 | 4 | 0.7 |
| 200–300 GeV | 2235 | 17.5 | 6 | 0.4 |
| Total | 18 224 | 100.2 | 12 | 1.3 |

of $(8.3 \pm 4.8)\times 10^{-5}$ (significantly less than the $\mu^-\mu^-/\mu^-$ ratio). We conclude that the background $\mu^-\mu^-$ events are dominated by second muons from $\pi$ or $K$ decay.[13] Our background with use of the data and procedures described above is $1.3 \pm 0.7$ such events in our sample. The probability of observing 12 events when 1.3 are expected is less than $10^{-7}$. Hence we conclude that the $\mu^-\mu^-$ signal is real. Table I gives the number of expected decay events corrected for geometrical acceptance as a function of energy.

The dimuon sample is divided into two groups, like-sign ($\mu^-\mu^-$) and opposite-sign ($\mu^-\mu^+$) events. The geometrical acceptance for these two groups is different in that $\mu^-$ ($\mu^+$) is focused (defocused) in the toroid spectrometer. The azimuthal acceptance for the $\mu^-\mu^-$ events can be calculated in a model-independent way since this acceptance is very high for the focusing $\mu^-$. On the other hand, $\mu^-\mu^+$-event acceptance is more model dependent because the $\mu^+$ is defocused and may exit from the side of the toroid. For this reason we choose to normalize the $\mu^-\mu^-$ events to the $1\mu$ events that could produce an observable second $\mu^-$ track.[14] The geometrically corrected numbers of events are given in Table I.

Figure 2 shows a comparison of the results of this experiment with those of other counter experiments. A strong neutrino-energy dependence is seen. Some of this dependence possibly arises from the $p_{\mu 2}^{\min}$ requirement; it could be due to threshold effects, if we assume that the muons come from heavy-particle decays. Most other experiments are at lower mean energies where the subtraction of $\pi$- and $K$-decay background is large. The high purity of our like-sign dimuon sample is due to the high-energy Fermilab quadrupole beam combined with a high-density steel target and the $p_{\mu 2}^{\min}$ requirement of 9 GeV. The ratio of background to prompt signal in this experiment is 0.12 while this same ratio for other experiments is typically greater than 0.8.[1]

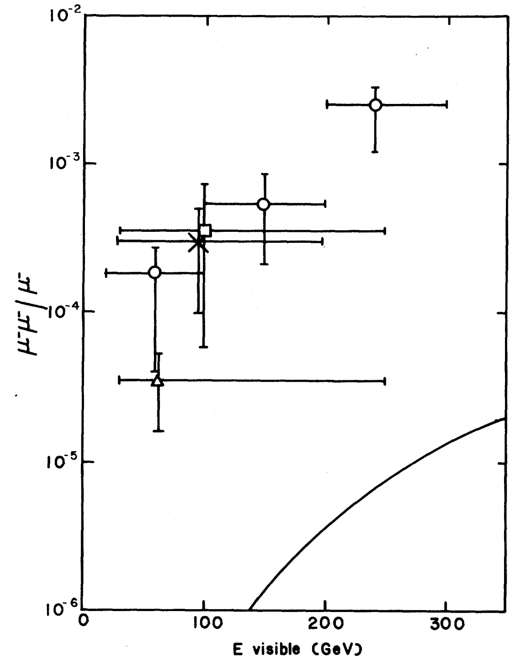


FIG. 2. Comparison of the dependence of the $\mu^-\mu^-/\mu^-$ ratio on visible energy observed in several counter experiments and a theoretical prediction of a first-order quantum-chromodynamics calculation for $c\bar{c}$ production (Ref. 15). The data references are this experiment, circles; Holder *et al.* (Ref. 2), crosses; deGroot *et al.* (Ref. 3), triangles; and Benvenuti *et al.* (Ref. 17), squares. This experiment requires $p_\mu^{\min} = 9$ GeV while the others have $p_\mu^{\min} = 10$ GeV.

A theoretical curve based on a first-order quantum-chromodynamics calculation of expected charm-anticharm production via gluon bremsstrahlung[15] is also shown in Fig. 2. It has been anticipated that higher-order corrections may significantly alter the absolute $c\bar{c}$ production rate but would not substantially affect the kinematic distributions.[7] The curve lies about two orders of magnitude below the observed data. Despite this very large discrepancy, $c\bar{c}$ production is still a possible source of like-sign events based on comparison of the qualitative features of $c\bar{c}$ production which we discuss.

Table II summarizes average quantities for the like-sign and opposite-sign events. The leading muon is defined as the negative muon with the greatest energy. Some general comments can be made from the comparisons shown in Table II. If the like-sign events originate from heavy-lepton decay, then $E_h$, the hadron energy, should be

TABLE II. Average quantities for $\mu^-\mu^+$ and $\mu^-\mu^-$ events. $E_{vis}=E_{\mu1}+E_{\mu2}+E_h$. $x_{vis}=2E_{\mu1}E_{vis}\sin^2(\frac{1}{2}\theta_{\mu1})/(E_{\mu2}+E_h)m_p$. $y_{vis}=(E_h+E_{\mu2})/E_{vis}$. $z_\mu=p_{\mu2}/(p_{\mu2}+E_h)$. $W$ is the invariant mass of the hadron system.

| Quantity | $\mu^-\mu^+$ | $\mu^-\mu^-$ |
|---|---|---|
| $E_{vis}$ (GeV) | $148\pm6$ | $179\pm19$ |
| $E_h$ (GeV) | $62\pm4$ | $101\pm14$ |
| $p_{\mu2}$ (GeV) | $19\pm1$ | $14\pm2$ |
| $p_{\perp2}{}^s$ (GeV) | $0.91\pm0.07$ | $0.63\pm0.14$ |
| $\varphi$ (deg) | $130\pm5$ | $131\pm8$ |
| $x_{vis}$ | $0.14\pm0.01$ | $0.22\pm0.07$ |
| $y_{vis}$ | $0.59\pm0.02$ | $0.63\pm0.05$ |
| $z_\mu$ | $0.33\pm0.02$ | $0.17\pm0.04$ |
| $W$ (GeV) | $11.3\pm0.4$ | $12.7\pm1.2$ |

small and $\varphi$, the azimuthal angle between the two muons, should be almost isotropic. Neither of these is observed. If the like-sign events originate from quarks heavier than charm, then $p_{\perp2}{}^s$, the momentum perpendicular to the struck-quark direction, would be larger for like-sign events. The $p_{\perp2}{}^s$ is seen to be even less than for the opposite-sign events. A cascade process, whether produced by a neutral- or charged-current process, could reduce the magnitude of this parameter. Quarks heavier than charm may also produce a more isotropic $\varphi$ distribution. The $\langle z_\mu\rangle$ for like-sign events is about one half the value for opposite-sign events, as would be expected for $c\bar{c}$ production. In general, the features demonstrated from these distributions are consistent with the source of the second muon being from the hadronic vertex and specifically from the decay of a charmed particle produced in associated production. One feature that may bear on the detailed production mechanism of these events is the value of $\langle x_{vis}\rangle$ shown in Table II.[16] The $\langle x_{vis}\rangle$ for opposite-sign dimuons is smaller than that for single muons, consistent with an appreciable contribution from sea quarks, while the $\langle x_{vis}\rangle$ of like-sign events is comparable to that of single-muon events.

In summary, this experiment has observed a direct like-sign dimuon signal with a background contamination which is much less than in previously published results. The ratio of $\mu^-\mu^-/\mu^-$ events rises with energy to a value of $(2.5\pm1.0)\times10^{-3}$ at $E_{vis}=250$ GeV. While the source of the like-sign dimuons is still not known, it is not likely that they originate from either heavy leptons or directly produced quarks heavier than charm. Associated charm-anticharm production is one possible source although the large relative rate is at variance with theoretical predictions.

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[8]Antineutrino-induced $\mu^-\mu^+$ events have not been removed from this sample. 17% of the induced $1\mu$ events are due to antineutrinos. Antineutrino-induced $1\mu$ events were removed from the $1\mu$ sample.

[9]See D. Buchholz, in *Proceedings of the Nineteenth International Conference on High Energy Physics, Tokyo, Japan, 1978*, edited by S. Homma, M. Kawaguchi, and H. Miyazawa (Physical Society of Japan, Tokyo, 1979), p. 332.

[10]R. Field, private communications.

[11]See K. Nishikawa *et al.*, Northwestern University Report No. NU78-52 (unpublished).

[12]We would like to thank J. S. Chima for giving us access to recent unpublished results from BEBC data. Earlier data and experimental details of this experiment can be found in P. C. Bosetti *et al.*, Nucl. Phys. B149, 13 (1979).

[13]Background muons are almost totally due to two-body decays of $\pi$'s or $K$'s. Three-body decays of charged and neutral $\pi$'s and $K$'s contribute less than 6% of the background events.

[14]The number of $1\mu$ events is reduced by the requirement that these events be able to produce an observable

second $\mu^-$ track. This is incorporated by requiring that the hadron shower have sufficient energy to produce a $\mu$ with momentum greater than 9 GeV and be momentum analyzable.

[15]This was obtained from Young *et al.*, Ref. 3, under the assumption that the semileptonic charm branching ratio was 10%.

[16]Young *et al.*, Ref. 3, suggest that asymptotically $x$ for events with $c\bar{c}$ production are the same as for all events.

[17]Obtained from Ref. 4 by assuming $\mu^-\mu^+/\mu^- = 0.65 \times 10^{-2}$.

# Excited $K^\pi = 0^+$ Rotational Band in $^{28}$Si

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An excited $K^\pi = 0^+$ band in $^{28}$Si which can be associated with the prolate Hartree-Fock solution has been observed in the reactions $^{25}$Mg$(\alpha, n\gamma)$ and $^{27}$Al$(p, \gamma)$. The $I^\pi = 0^+$ through $6^+$ band members have been located at $E_x = 6691$, 7381, 9164, and 11 509 keV, respectively. Strong distortion is indicated from $B(E2)$ values, resulting in $|Q_0| = 876^{+110}_{-85}$ mb.

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Hartree-Fock calculations of $^{28}$Si yield oblate and prolate solutions which are nearly degenerate. Das Gupta and Harvey[1] proposed at an early stage that $K^\pi = 0^+$ rotational bands, which are based on the ground and 6691-keV states, be associated with the prolate and oblate solutions, respectively. Only the ground-state band has been observed so far[2] and its oblate nature has been confirmed.[3,4] In this work we present evidence of an excited $K^\pi = 0^+$ band from an investigation of the reactions $^{25}$Mg$(\alpha, n\gamma)$ and $^{27}$Al$(p, \gamma)$.

The $(\alpha, n\gamma)$ measurements were performed by bombarding a 300-$\mu$g/cm$^2$ self-supporting $^{25}$Mg foil with 14.5-MeV $\alpha$ particles. The 40-nA beam was provided by the 7-MV Van de Graaff accelerator of the University of Freiburg. Neutron-$\gamma$-ray coincidences were measured with two 120-cm$^3$ Ge(Li) detectors and a neutron time-of-flight (TOF) spectrometer at zero degrees with respect to the beam at a distance of 2.5 m from the target. The TOF spectrometer consists of nineteen liquid-scintillation detectors in a quasiannular array. An identical spectrometer with only seven detectors has been used previously.[5,6] Hence information concerning the quality of neutron and $\gamma$-ray spectra can be obtained from that work.

Complete $n$-$\gamma$ angular correlations were measured at six angles. Several hitherto unknown $^{28}$Si levels of high spin were observed, among them an 11509 keV level. Its decay mode is given in Table I. The full Doppler shift of the 11 509 → 6889 keV transition yielded a reliable lifetime limit $\tau(11\,509) < 30$ fs. (There was no evidence of a possible 11 509 → 6879 keV transition which would affect the life-time measurement.) The $n$-$\gamma$ angular correlation of the same transition has (Fig. 1) the typical shape of a stretched $(I \rightarrow I-2)$ quadrupole transition, thus suggesting a $I = 6$ assignment to the 11 509 keV level. A simultaneous fit to the correlations of both the 11 509 → 6889 and 11 509 → 9164 keV transitions yields at a 0.1% confidence limit a $I = 6$, 4 assignment to the 11 509 keV level and a $I^\pi = 4^+$ assignment to the 9164 keV level, which hitherto had[7] $I^\pi = 3^-, 4^+$. The lifetime limit of the 11 509 keV level implies positive parity of the level because otherwise it would have $M2$

TABLE I. Branching ratios (%) and multipole transition rates $B(\lambda, \mu)$ (Weisskopf units) of rotational states.

| $E_f$ (keV) | $I_f^\pi$ | Branch | $B(\lambda, \mu)$ | |
|---|---|---|---|---|
| | | 11 509 keV, $I^\pi = 6^+$ state | | |
| 9164 | $4^+$ | $24 \pm 2$ | $> 18$ | $(E2)$ |
| 6889 | $4^+$ | $68 \pm 3$ | $> 1.7$ | $(E2)$ |
| 4617 | $4^+$ | $8 \pm 2$ | $> 0.03$ | $(E2)$ |
| 8543 | $6^+$ | $< 2$ | $< 2 \times 10^{-3}$[a] | $(M1)$ |
| | | 9164 keV, $I^\pi = 4^+$ state | | |
| 7417 | $2^+$ | $4.5 \pm 0.5$ | $11.5^{+3.6}_{-2.7}$ | $(E2)$ |
| 7381 | $2^+$ | $13.5 \pm 1.0$ | $32^{+8}_{-6}$ | $(E2)$ |
| 6889 | $4^+$ | $2.9 \pm 0.3$ | $(20 \pm 5) \times 10^{-4}$ | $(M1)$ |
| 6879 | $3^-$ | $1.9 \pm 0.3$ | $(43 \pm 12) \times 10^{-6}$ | $(E1)$ |
| 4617 | $4^+$ | $30.8 \pm 0.4$ | $(27 \pm 4) \times 10^{-4}$ | $(M1)$ |
| 1778 | $2^+$ | $46.4 \pm 2.0$ | $(9 \pm 2) \times 10^{-2}$ | $(E2)$ |

[a]We assume $B(E2) < 36$ Weisskopf units for the 11 509 → 9164 keV transition.

 