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Observation of Prompt Like-Sign Dimuon Production In Neutrino Reactions

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ABSTRACT

We report on the observation of 12 like-sign ($\mu^-\mu^-$) neutrino-induced dimuon events with muon momenta greater than 9 GeV. The empirically determined background from π 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 $(2.5 \pm 1.0) \times 10^{-3}$ at $E_\nu = 250$ GeV.

A unique tool to investigate new flavor production by the weak interactions has been multimuon production by neutrinos and anti-neutrinos. 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, are much less well established but perhaps very significant. For the first time, this experiment establishes the existence of prompt like-sign dimuon events from neutrino interactions. For such events, the second μ- cannot come from the decay of any known singly produced quark (i.e. u, c, $\bar{d}$, $\bar{s}$, or $\bar{b}$). Some calculations have been made using heavy quark cascades, heavy leptons[2] or associated charm-anticharm production.[3,4] 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 background in this experiment is significantly lower than previous measurements[1] due to the high density of the detector, the higher neutrino energy spectrum, and the kinematic restrictions on the observed muons. The experiment was performed at Fermilab using the quadrupole triplet beam with 400 GeV incident protons. The detector consisted of a dual density steel target (160 tons), a steel hadron adsorber (224 tons), and magnetized solid steel toroids (440 tons) for muon momentum analysis. The target was composed of eighty 1.5m x 1.5m x 10cm thick steel plates interspersed with liquid scintillation counters. It was arranged in two densities (differing by a factor of two) to check our empirical estimate of non-prompt 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 (1.5m x 3m) for hadron shower containment. The target was followed by a hadron absorber consisting of twenty-eight 3m x 3m x 10cm thick steel plates interspersed with scintillation counters every 10 cm of steel and spark chambers every 20 cm of steel. The 1.8m 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 80cm were used to track the muon through the spectrometer. The hadron energy was determined with a fractional accuracy of $1.1/\sqrt{E}$ (GeV) and the muon momentum measured to 10 percent.

The trigger requirements were 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_μ^{min}) to reduce π and K decay non-prompt 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 non-sampled 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 19036 (17203) $1\mu^-$ events, 47 (45) $\mu^-\mu^+$ events, 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 1μ and 2μ samples.

The use of the dual density target in separating the prompt and non-prompt sources of opposite-sign dimuon events with lower p_μ^{min} events has been reported elsewhere.[5] There the measured non-prompt rate agreed with the calculated rate within 15%. In the present $\mu^-\mu^-$ sample the statistics are not adequate to separate the prompt and non-prompt contributions by a comparison of rates in the two different density targets. Rather we rely on the same calculation of the expected π 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[6] which is based on fits to neutrino-induced hadron final state data as measured in neon bubble chamber experiments. This program provides 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 μ decay rate from subsequent interactions of these hadrons is determined using direct measurements of π-Fe interactions from an experiment[7] where both the prompt and non-prompt 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 ν Ne distributions are the same as the ν-Fe distributions. At high hadron energies where the bubble chamber data are relatively poor statistically the Field-Feynmann parameterization is assumed to be correct. This assumption has been cross checked by using new bubble chamber data[8] at higher energies directly instead of the Field-Feynmann 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 assuming 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_μ^{min} requirement reduced to 3.0 GeV, we observe three 3μ events which corresponds to a $3\mu/1\mu$ 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 π or K decay. Our empirical determination described above gives 1.3 ± 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 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 μ^- ($\mu+$) is focused (defocused) in the toroid spectrometer. The acceptance for the $\mu^-\mu^-$ events can be calculated in a model independent way since the acceptance is very high for the μ^- whereas the $\mu^-\mu+$ events are 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 1μ events that could produce an observable second μ^- track. 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 π and K decay background is large. The high purity of our like-sign dimuon sample is due to the high energy FNAL 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]

A theoretical curve based on a first-order QCD calculation of expected charm-anticharm production via gluon bremsstralung[9] is also shown in Figure 2. It has been anticipated that higher order corrections may significantly alter the absolute $c\bar{c}$ production rate but would not substantially effect the kinematic distributions.[4] 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 small and ϕ, the azimuthal angle between the 2 muons, should be almost isotropic. Neither of these is observed. If the like-sign events originate from quarks heavier than charm, then $p^s_{\perp 2}$, the momentum perpendicular to the struck quark direction, would be larger for like-sign events. The $p^s_{\perp 2}$ is seen to be even less than for the opposite-sign events. A cascade process could reduce the magnitude of this parameter. 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. 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

$(2.5 \pm 1.0) \times 10^{-3}$ 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.

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TABLE I

Event Statistics
(corrected for geometrical acceptance and with $p_{\mu}^{min} = 9$ GeV)

Energy Events	20-100	100-200	200-300	TOTAL
1μ	9809	6180	2235	18224
$\mu^-\mu^+$	22.8	59.9	17.5	100.2
$\mu^-\mu^-$	2	4	6	12
$\mu^-\mu^-$decay	0.2	0.7	0.4	1.3

TABLE II

Average Quantities for $\mu^-\mu^+$ and $\mu^-\mu^-$ Events

Quantity	$\mu^-\mu^+$	$\mu^-\mu^-$
E_{vis} (GeV)	148±6	179±19
E_h (GeV)	62±4	101±14
$p_{\mu 2}$ (GeV)	19±1	14±2
$p_{\perp 2}^{s}$ (GeV)	0.91±0.07	0.63±0.14
ϕ (deg)	130±5	131±8
x_{vis}	0.14±0.01	0.22±0.07
y_{vis}	0.59±0.02	0.63±0.05
z_{μ}	0.33±0.02	0.17±0.04
W (GeV)	11.3±0.4	12.7±1.2

$E_{vis} = E_{\mu 1} + E_{\mu 2} + E_h$

E_h is the hadron energy

$p_{\mu 2}$ is the momentum of the second muon

$p_{\perp 2}^{s}$ is the momentum of the second muon perpendicular to the hadron shower direction

ϕ is the azimuthal angle between the two muons projected on the plane perpendicular to the neutrino

$x_{vis} = 2E_{\mu 1} E_{vis} \sin^2(\theta_{\mu 1}/2)/(E_{\mu 2}+E_h)m_p$

$y_{vis} = (E_h + E_{\mu 2})/E_{vis}$

$z_{\mu} = p_{\mu 2}/(p_{\mu 2} + E_h)$

W is the invariant mass of the hadron system

FOOTNOTES

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[6] R. Field, private communication.

[7] Data of Fermilab experiment 379.

[8] 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 Bossetti, et al., Nucl. Phys. B149, 13 (1979).

[9] This was obtained from Young et al., ref. 3, assuming the semileptonic charm branching ratio is 10%.

[10] M. Holder et al., Phys. Let., 70B, 396 (1977).

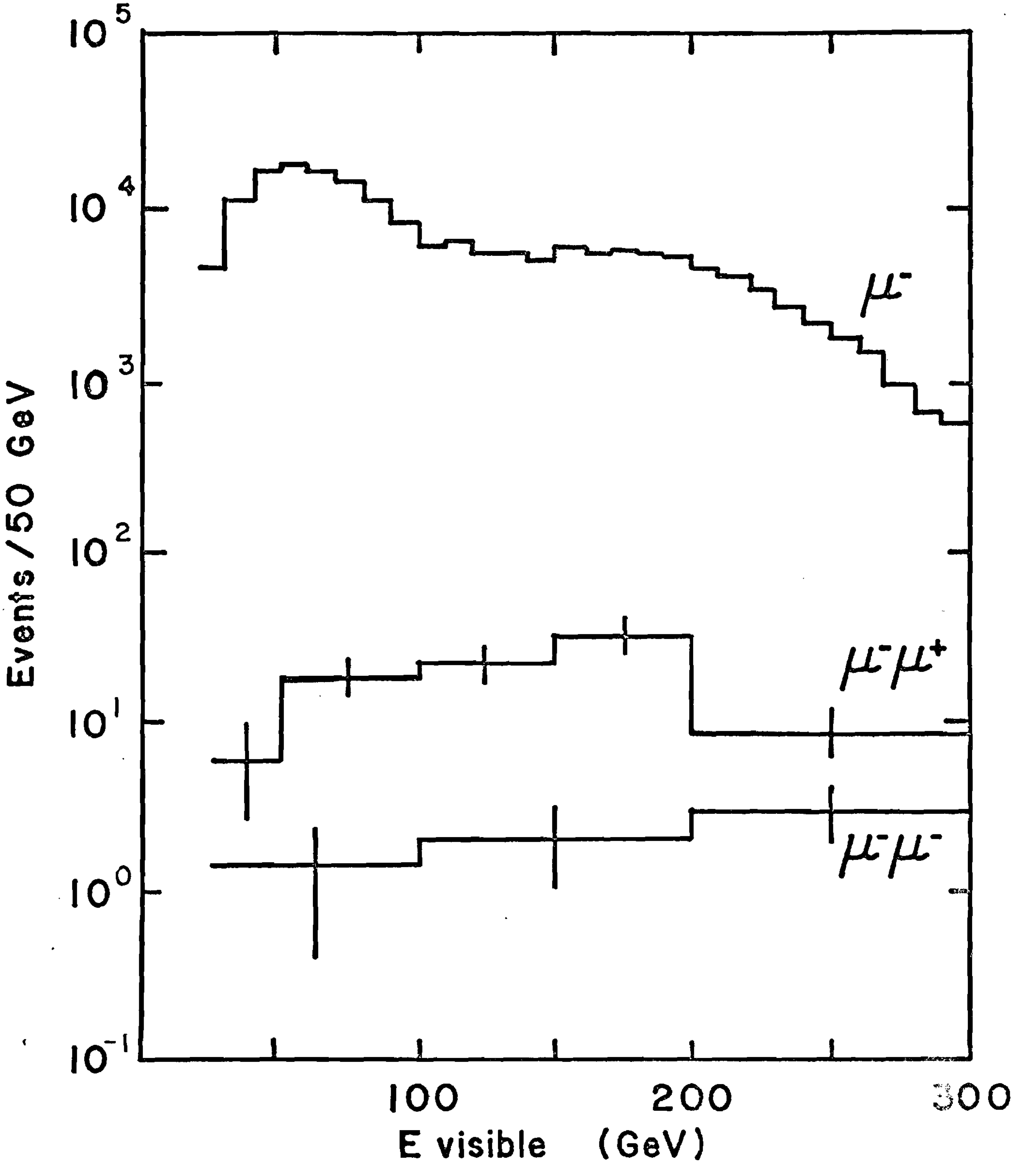
[11] J. G. H. deGroot et al., Phys. Let., 86B, 103 (1979).

[12] Obtained from A. Benvenuti et al., Phys. Rev. Let., 41, 725 (1978) by assuming $\mu^-\mu^+/\mu^- = 0.65 \times 10^{-2}$.

FIGURE CAPTIONS

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

Figure 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 QCD calculation for $c\bar{c}$ production.[9]



10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
Events / 50 GeV
100
200
300
E visible (GeV)
μ^-
$\mu^-\mu^+$
$\mu^-\mu^-$

FIGURE 1.

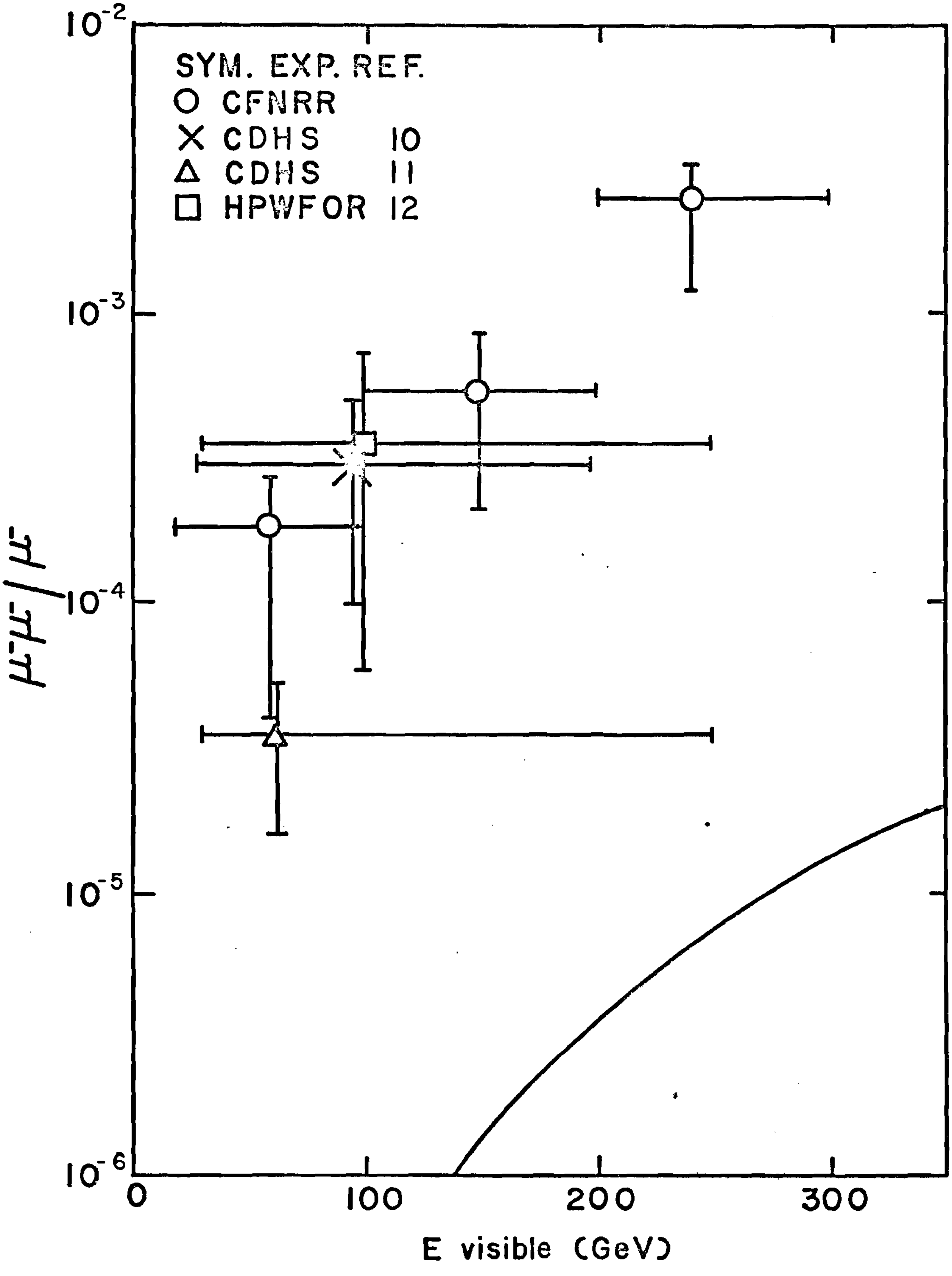

SYM. EXP. REF.
○ CFNRR
× CDHS 10
△ CDHS 11
□ HPWFOR 12
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$\mu^-\mu^-/\mu^-$
0
100
200
300
E visible (GeV)

FIGURE 2.