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RATE OF DIMUON PRODUCTION FROM NEUTRINOS AND ANTINEUTRINOS AT HIGH ENERGY

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ABSTRACT

We present data on dimuon production rates from neutrinos and antineutrinos in the energy range 45 to 205 GeV. The measurements were made using the Fermilab narrow-band beam. At higher energies ($\gtrsim$ 100 GeV), the dimuon production rates relative to single muon production for events within our kinematic cuts are about 1%. The numbers are consistent with calculations of GIM (4-quark) models and do not require the introduction of additional quarks.

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It has been recognized for some time that neutrino induced events with more than one lepton in the final state constitute an important tool for recognizing thresholds of new hadronic or leptonic states. It is expected, for example, that states containing net charm will decay leptonically to produce such events. It is not yet clear, however, whether the dimuon[1 2] or μe[3] signals observed thus far are simply a consequence of charm or whether additional particles with other new quantum numbers are required.

This report describes results[4] on high energy dimuon production by neutrinos and antineutrinos. These data were obtained using the Caltech-Fermilab neutrino detector[5] and the Fermilab narrow-band neutrino beam.[6] They were taken over a wide range of well defined incident neutrino energies (E_ν), between 45 and 205 GeV. Several features of the experiment are particularly relevant to dimuon studies. They include a) the sign-selected dichromatic beam, and b) a dense target-calorimeter.

Since the beam is sign selected, neutrino and antineutrino events are separated at the level of a few percent. At each of the secondary beam settings, momentum selection produces incident neutrinos which fall into two distinct energy bands (ν_π, ν_K), each with means that are known to ±1.5%.[7] As a consequence, the energy dependence of the dimuon signal can be investigated. Also, we can determine whether significant energy is carried away by unseen neutrinos.

The target-calorimeter has a high density, about 4 gm/cm^3, which minimizes extra muons from the decay of pions or kaons

in the hadron shower. The target serves as the muon-identifier and is well instrumented to study muons down to an energy (~2 GeV) where muons and pions can just be distinguished.

Events are selected from an 83-ton fiducial volume inside the target-calorimeter. Scintillation counters located every 10 cm of steel are used to measure E_H, the final state hadron energy, using calorimetry techniques.[8] The angles of the final state muons (θ_μ) are determined with spark chambers situated every 20 cm of steel inside the target. A downstream spectrometer consisting of a steel toroid and associated spark chambers is used to measure the momentum of muons which traversed it. The small acceptance of the toroidal magnet is an important limitation of the apparatus. Many identified second muons do not traverse this spectrometer because they are too low in energy or at too large an angle. Consequently, more complete kinematic information is only determined for the fraction of the events in which both muons traverse the magnet.

Table I presents a summary of the raw numbers of events observed within the fiducial volume of this experiment. Only events in which one or more muons traverse the spectrometer were chosen. The distinctive features of the events are: (1) the dimuon rate for penetrations greater than 1.8 m is roughly 1% of the single muon rate; (2) the dimuon rates from neutrino and anti-neutrino interactions are similar to a factor of two; and (3) approximately 10% of the dimuon events have muons of the same charge. For penetrations greater than 2.8 m (corresponding to a muon energy of 4 GeV), the dimuon rate (and background rate) decrease

by about a factor of two from the rate for a penetration requirement of 1.8 m.

The size of the event sample is reduced about a factor of 4 by requiring the second muon to traverse the toroid. This illustrates that the second muon typically has low energy and large angle. The kinematic features of the 20 opposite-sign dimuon events, within the statistical limitation of the sample, are similar to those reported previously on different data samples.[1] [2] We concentrate here on the more inclusive 95 events in entry (b), which are statistically more significant and have fewer kinematic restrictions. In particular, we investigate the relative dimuon rates induced by neutrinos and antineutrinos.

A major limitation in such a measurement is any background which simulates a second muon. One potential source of background is a single muon event in which charged secondaries in the hadronic shower have such a long penetration that they appear to be a track in the spark chambers. The counters imbedded in the steel permitted the investigation of this effect. Such a penetrating hadron shower, in general, would produce pulse-heights which are not typical of the passage of two minimum ionizing particles. For penetrations greater than 1.5 m of steel, these events are consistent with having a single extra muon. The penetration cut applied here is 1.8 m of steel.

With this cut, the most likely background source of dimuon events is an ordinary charged current event with an extra muon

resulting from the decay of a pion or kaon produced in the hadronic cascade. Unfortunately, we have no direct measure of this non-prompt background. To estimate it, we use a Monte Carlo program which simulates the complete cascade.[9] The resulting hadron decay probability curves are folded together with the measured E_H distributions from the single muon events at each incident neutrino energy to obtain the expected number of background events as a function of the second muon penetration. The procedure is essentially identical to a calculation used for previous data by this group.[1] Because some assumptions in the calculation have not been experimentally verified, we quote a 100% error on the background subtraction.

At each beam setting, we have separated the dimuon events into the two distinct energy bands (ν_π, ν_K) according to their total observed energy. This division is appropriate if the unmeasured muon and any unseen neutrinos carry only a small fraction of the incident neutrino energy. As a check, the average observed energy of dimuon events is compared with the average observed energy of single muon events at each energy. The means of the total energy for dimuon events were found on the average to be within 10% of the means for single muon events. We conclude that the dimuon events typically do not have a large amount of unseen energy.

The ratios of dimuon to single muon event rates ($R \equiv \sigma_{\mu\mu}/\sigma_{\mu}$), corrected for the azimuthal detection efficiency, are shown in Fig. 1. The data have been corrected solely for the azimuthal detection efficiency since any further correction requires a knowledge of the dimuon production mechanism. All events are included in the plots in which: a) the first muon traverses the spectrometer ($\theta_{\mu 1} < 100$ mrad and $E_{\mu 1} > 6$ GeV); and b) the penetration of the second muon is greater than 1.8 meters of steel ($E_{\mu 2} > 2.5$ GeV, and $\theta_{\mu 2} < 360$ mrad).

The dashed curves in Fig. 1 show our estimate of the non-prompt background from pion and kaon decay described previously. The data points have already been corrected by this estimate. The inner error bars reflect the statistical uncertainty; the outer bars have the estimated systematic uncertainty folded in quadrature. The calculated background is much smaller than R and does not easily account for its increase with energy.

Also shown in these figures are the ratios calculated from a specific GIM model in which the second muon comes from the prompt decay of a charmed hadron.[10,11] The curves have been normalized to the neutrino data at 185 GeV. Although all of the acceptance limitations are not included in the curves, such effects should become small as the energy becomes much larger than threshold.[11] In the case of charm, the relative contribution to neutrino and antineutrino dimuon events above about 100 GeV should not be seriously biased. The calculated energy dependences of R agree reasonably well with the data.

In Fig. 1b, we also plot the expected R for antineutrino induced events assuming a right-hand coupled b-quark with mass 5 and 7 GeV. The leptonic branching ratio for the b-quark is assumed equal to that of charm. B-quark masses greater than about 7 GeV cannot be ruled out. Massive b-quarks below 5 GeV in this model appear very unlikely.

In summary, we see dimuon production in both neutrino and antineutrino data over a wide range of energies. The azimuthally corrected neutrino and antineutrino dimuon production rates relative to the single muon production rates reach about 1% at high energy. The energy dependence of the dimuon signal is consistent with a GIM model of charm production. We also conclude that energy carried away by unseen leptons is, on the average, less than 10% of the total energy.

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TABLE CAPTIONS

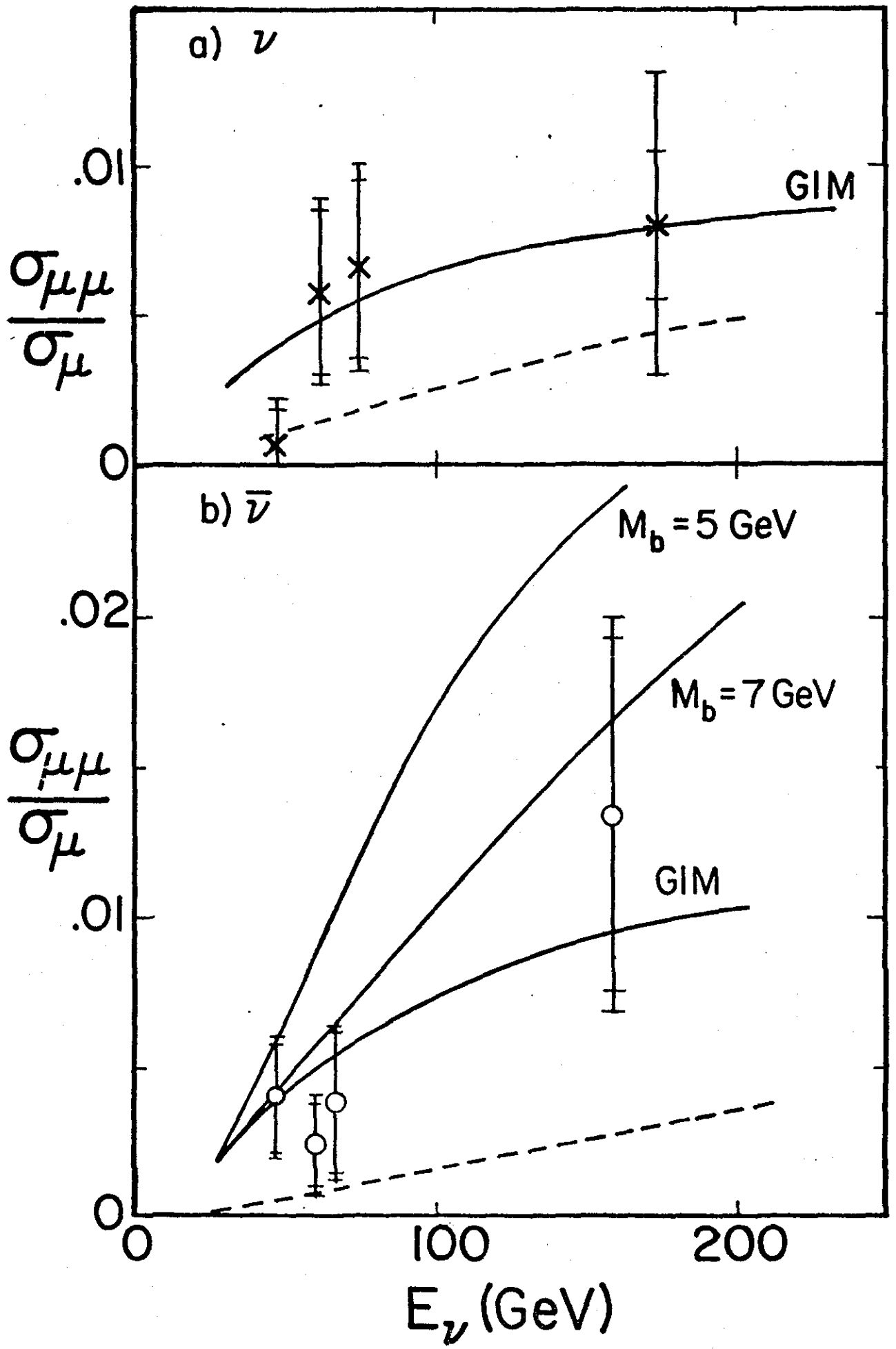
Table I: A summary of the raw numbers of events observed in this experiment for which at least one muon traverses the spectrometer for various stages in the event selection process.

TABLE I

	Number of ν Induced Events	Number of $\bar{\nu}$ Induced Events	Total
(a) Single μ events	7774	5186	12960
(b) 2μ events in which the second muon penetrates more than 1.8 meters of steel	67	28	95
(c) Events with both muons momentum analyzed	14	8	22
(d) Same-sign muons	2	0	2

FIGURE CAPTIONS

Figure 1: The ratio, R, of the dimuon production cross section ($\sigma_{\mu\mu}$) to the single muon production cross section (σ_{μ}) for a) neutrino and b) antineutrino events is plotted as a function of the average incident neutrino energy. For statistical reasons, the data for E_{ν} = 125, 171, and 205 GeV and $E_{\bar{\nu}}$ = 129, 168, and 188 GeV have been combined. The estimated background (the dashed curves) has <u>already</u> been subtracted from the data shown. The solid curves (labeled GIM) are calculated from a GIM (4-quark) model normalized to the 185 GeV neutrino data. R expected for antineutrino events assuming a right-hand coupled b-quark with masses 5 and 7 GeV are also shown.


a) ν
.01
0
GIM
σμμ / σμ
b) ν̄
M_b = 5 GeV
.02
M_b = 7 GeV
σμμ / σμ
GIM
.01
0
0
100
200
E_ν (GeV)