Fermi National Accelerator Laboratory

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Measurement of Same-Sign Dimuon Production in High-Energy Neutrino Interactions*

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Abstract

We present rates for same-sign dimuon production in neutrino-iron interactions with energies of 30-600 GeV. We find 101 neutrino and 15 anti-neutrino induced same-sign dimuons with muon momenta above 9 GeV/c. A detailed calculation indicates that the overall level and kinematic distributions of conventional backgrounds are consistent with the data. There is no convincing indication of new physical processes.

Historical Perspective

Dimuon production in ν interactions has been a topic of study since the early 1970's. When opposite-sign dimuons were first reported in 1974[1], the mechanism for their production was not understood. With the discovery of the J/ψ in that same year, the production of opposite-sign dimuons could then be attributed to the creation of a charmed quark and its subsequent semi-leptonic decay into a muon (see Figure 1a). The rate of production is approximately .005 per charged-current interaction at neutrino energies above 100 GeV and muon momentum > 9 GeV/c, and is well understood within the context of the standard model [2].

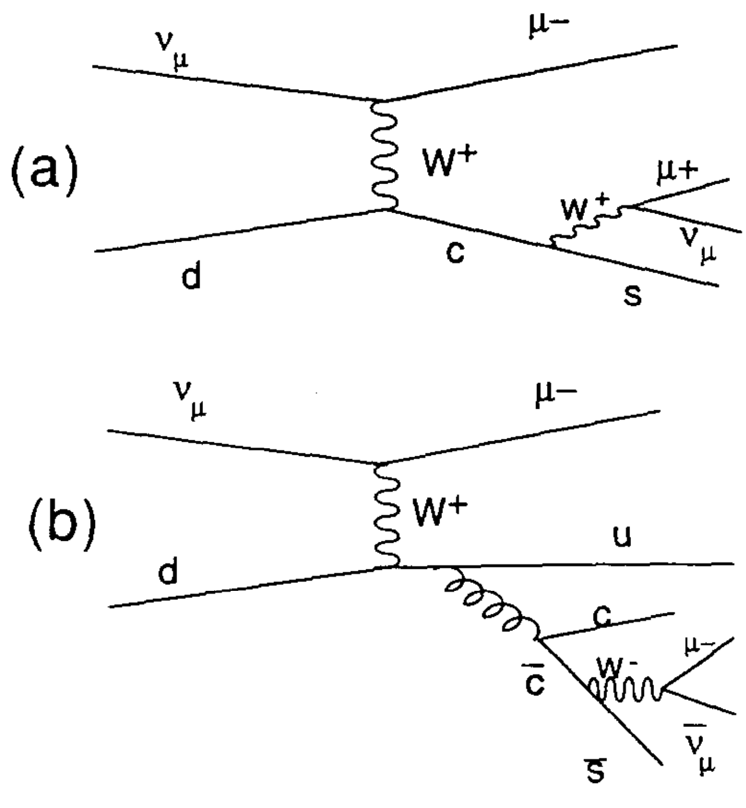


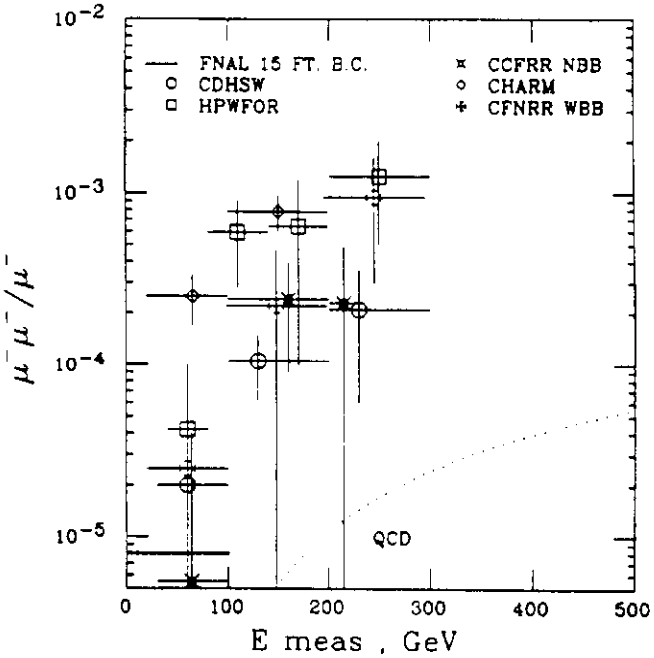
Figure 1: Quark diagrams for a) opposite-sign dimuon production b) perturbative QCD same-sign dimuon production.

Same-sign dimuons, which were first reported in 1975[3], have continued to be a subject of controversy. Unlike their opposite-sign counterparts, there is no leading quark diagram to explain their production. They are expected to be produced by the decay of π's and K's into muons in the hadron shower of charged-current events. This source of same-sign dimuons is called "non-prompt" because the second muon is not produced from the leading quark. Many experiments have reported a signal which is larger than expected from this mechanism[4]. Figure 2 shows the acceptance corrected rates of same-sign dimuons with respect to charged-current events after subtraction of the π/ K background. Since the "non-prompt" background has been subtracted, these rates are called "prompt".

A possible explanation for the prompt same-sign dimuon rate are perturbative QCD processes such as gluon bremsstrahlung of a charm anti-charm pair(Figure 1b), which predicts a rate that is on the order of 10^{-5} per charged-current interaction[5,6,7] at neutrino energies above 100 GeV and muon momentum > 9 GeV/c. A typical first order QCD $c\bar{c}$ gluon bremsstrahlung prediction is included in Figure 2. The predicted rate is subject to parameter choices such as the mass of the charm quark, and can vary as much as an order of magnitude. Other QCD processes such as bottom production are expected to be at the level of 10^{-5} or smaller. The measured experimental rates are up to thirty times (2-3 σ) higher than the predicted perturbative QCD rate. Furthermore, there is an indication from the data that the experimental rate may be rising as a function of neutrino energy.

The major difficulty with measuring the prompt same-sign dimuon rate is that one must first subtract the large background due to conventional sources such as charged-current interactions with a second muon produced from a π or K decay in the hadron shower. At least two-thirds of the same-sign dimuons detected in every same-sign dimuon experiment can be attributed to π/K decay. This background decreases with increasing detector density.

Figure 2: Published prompt same-sign dimuon production rates as a function of measured neutrino energy ($E_{meas} = E_{hadronshower} + E_{\mu_1} + E_{\mu_2}$). All have a 9 GeV/c cut on muon momentum except for the CHARM (4.0 GeV/c) the FNAL 15 ft. bubble chamber (4.0 GeV/c) and HPWFOR (10 GeV/c) points. The FNAL 15 ft. bubble chamber point is a 90 % confidence level upper limit for μ e. The dotted line represents a typical first order QCD calculation from reference 5.



The CCFR detector in the Fermilab Tevatron quadrupole triplet ν beam line is in a position to shed new light on the same-sign dimuon controversy. It is an experiment with high statistics using a high density detector, in a beam line that has doubled the available energy of previous experiments.

Beamline and Experiment

The quadrupole triplet beam line at the Fermilab Tevatron produced ν and $\bar{\nu}$ (ratio 2.5:1) from the decay of π's and K's from 800 GeV proton- beryllium interactions. Quadrupole magnets were used to maximize the flux of high energy π/K secondaries. However, there was no sign selection. The measured energy spectrum of charged-current events in the CCFR detector from the 1985 run is shown in Figure 3.

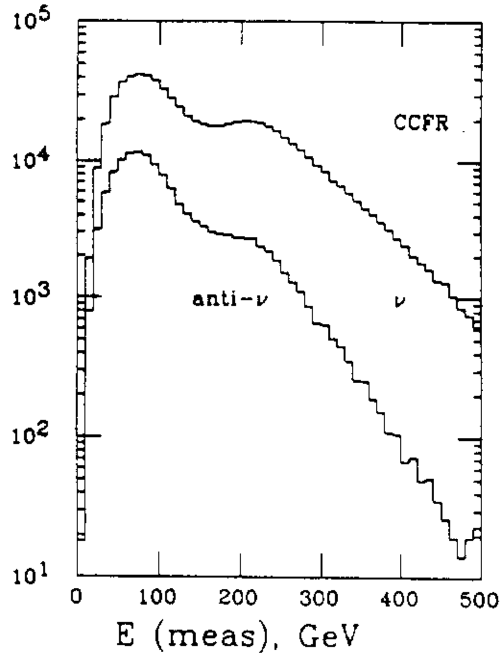


Figure 3: Measured energy spectrum for ν and $\bar{\nu}$ charged-current events from the 1985 Fermilab run.

The CCFR detector consisted of two parts: a high density target calorimeter followed by a toroidal muon spectrometer (see Figure 4). The 690 ton target calorimeter (dimensions $3.1 \times 3.1 \times 16.5$ m^3) was instrumented with liquid scintillation counters separated by 10 cm of steel and drift chambers separated by 20 cm of steel. The muon spectrometer contained three toroidal magnets (total transverse momentum kick of 2.4 GeV/c), drift chambers for muon tracking, and acrylic counters for event triggering and timing. The output of the target and toroid scintillation counters was read into a buffered ADC system. The drift chamber system in the toroid consisted of five banks of five drift chambers with no material between chambers in a given bank. Two of the drift chamber banks were located 3m and 7m downstream of the toroids in order to increase the lever arm for measuring muon momentum. An independent three parameter fit to muon track segments in each bank of toroid drift chambers determined the slope, intercept, and arrival time, which enabled us to measure the interaction time of a charged-current event with a resolution of 5 ns. This timing determination was possible because the drift chambers had a position resolution of 250 μm (with a drift velocity of 52μm/ns) and were read out by a multi-hit TDC system which had a precision of 4 ns. The scintillation counters in the target and the toroid were also read out by the TDC system. The timing information from the counters gave an independent measurement of the event time, which was very useful in eliminating the dimuon background from coincident charged-current interactions.

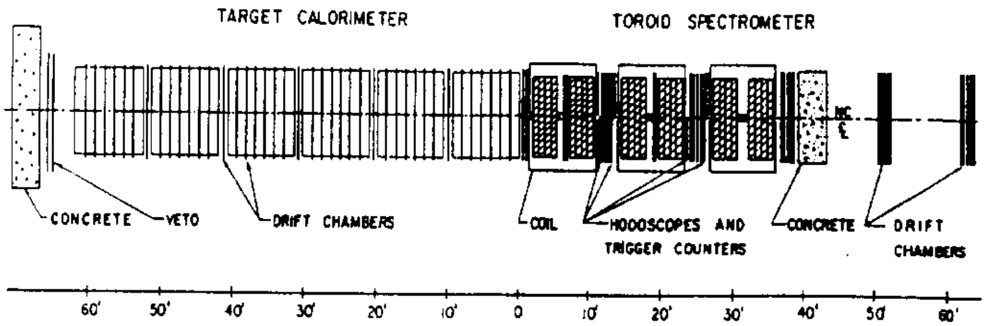


Figure 4: Schematic of the CCFR detector. The neutrino enters from the left. The calorimeter has a RMS resolution of $\delta E/E = .89/\sqrt{E(GeV)}$ while the muon momentum resolution is $\delta P/P$=11%

Data Selection

From February 1985 to August 1985, we collected 1.7 million charged-current events with a muon traversing our toroid spectrometer. For our analysis, we required certain fiducial cuts to assure that the hadron shower was contained in the target (reducing

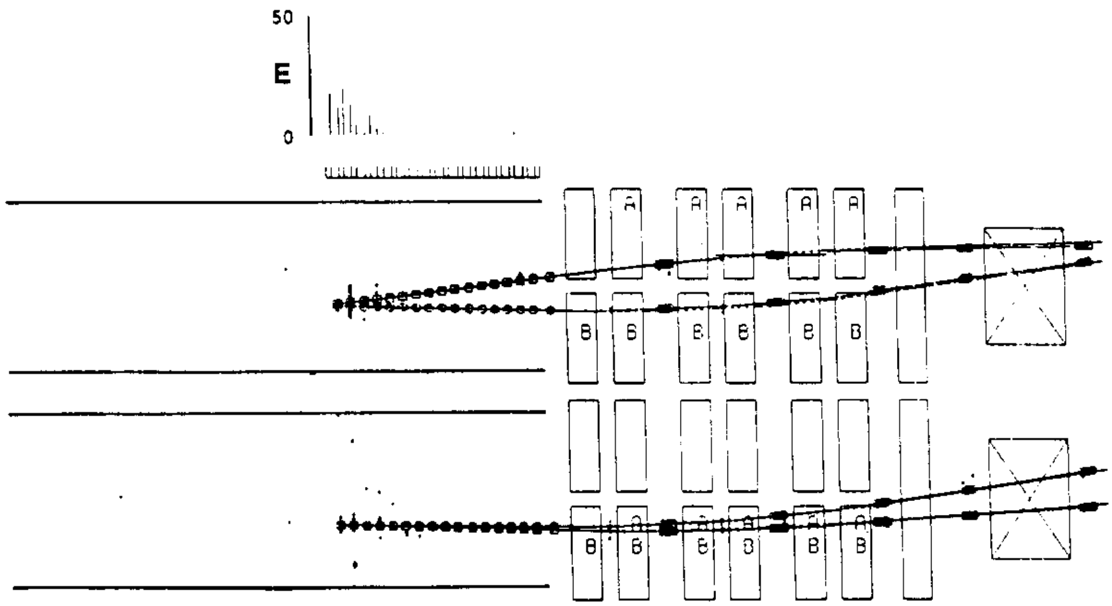


Figure 5: A same-sign $\bar{\nu}$ induced dimuon event in the CCFR detector. Upper view is vertical, lower view is horizontal. Histogram shows pulse height in calorimeter counters. Curves represent fitted muon tracks using drift chamber hits in the calorimeter and toroid spectrometer. The muon momenta are 46 and 33 GeV/c at the vertex; the hadron energy is 70 GeV. The time difference between the two muons is measured to be 1.3 ns.

the fiducial volume from 690 to 400 tons), and required that the muon pass through the good field region of the toroid. We required that a muon have a minimum momentum of 9 GeV/c at the event vertex; muons of less energy were not likely to penetrate the target and first toroid and hence were difficult to momentum analyze. The 9 GeV/c muon momentum requirement also enabled us to make a direct comparison of our data to other same-sign dimuon experiments. After these analysis cuts there were 712,000 ν and 140,000 $\bar{\nu}$ charged-current interactions. For the dimuon selection, we required that both muons satisfy our single muon cuts. In addition, the two muons must have a transverse distance of closest approach at the event vertex of < 15 cm and the difference in time between the two muons must be less than 28 ns (to ensure that both muons were in the same 18.8 ns r.f. bucket or in adjacent r.f. buckets). To reduce the background from misidentified trimuons, we required that the event not have a third muon of momentum greater than 3.1 GeV/c. Muons with less momentum than this are obscured by the shower and must be subtracted statistically from the event sample. There were 1922 dimuons that satisfied these criteria, of which 116 were same-sign dimuons (101 ν induced and 15 $\bar{\nu}$ induced). Figure 5 shows an event display of a same-sign dimuon in the CCFR detector.

Backgrounds to Same-Sign Prompt signal

Three established sources of same-sign dimuon production must be subtracted from the sample to obtain the level of prompt dimuon production: overlays (charged-current interactions coincident in space and time), trimuon events with two momentum analyzed muons and one muon obscured by the hadron shower, and charged-current events with a hadron shower π or K decaying into a muon (π/K decay).

The background contribution from overlays came from coincident charged-current events which satisfied our analysis cuts: a transverse distance of closest approach (DCA) of less than 15 cm and a time difference (δt) of less than 28 ns. Figures 6a and 6b show the DCA distribution and δt distribution for events satisfying all the two muon analysis cuts, except for the DCA and δt requirement. The peaks at δt=0 and DCA=0 contain legitimate dimuon events while the continuum represent overlays. The shaded region of Figure 6a shows the DCA events with δt less than 28 ns ("in time") and the unshaded shows $\delta t > 28$ ns ("out of time"). A clear separation of dimuons and overlays was observed. To estimate the overlay background for DCA < 15 cm we scaled the "out of time" DCA events to "in time" DCA events by the relative number of r.f. buckets (28 versus 2) and predicted a background of .5 events (.4 ν and < .1 $\bar{\nu}$) with DCA < 15 cm and 20 events with DCA > 15 cm. This agreed well with the measured 23 events with DCA > 15 cm in the "in time" DCA plot.

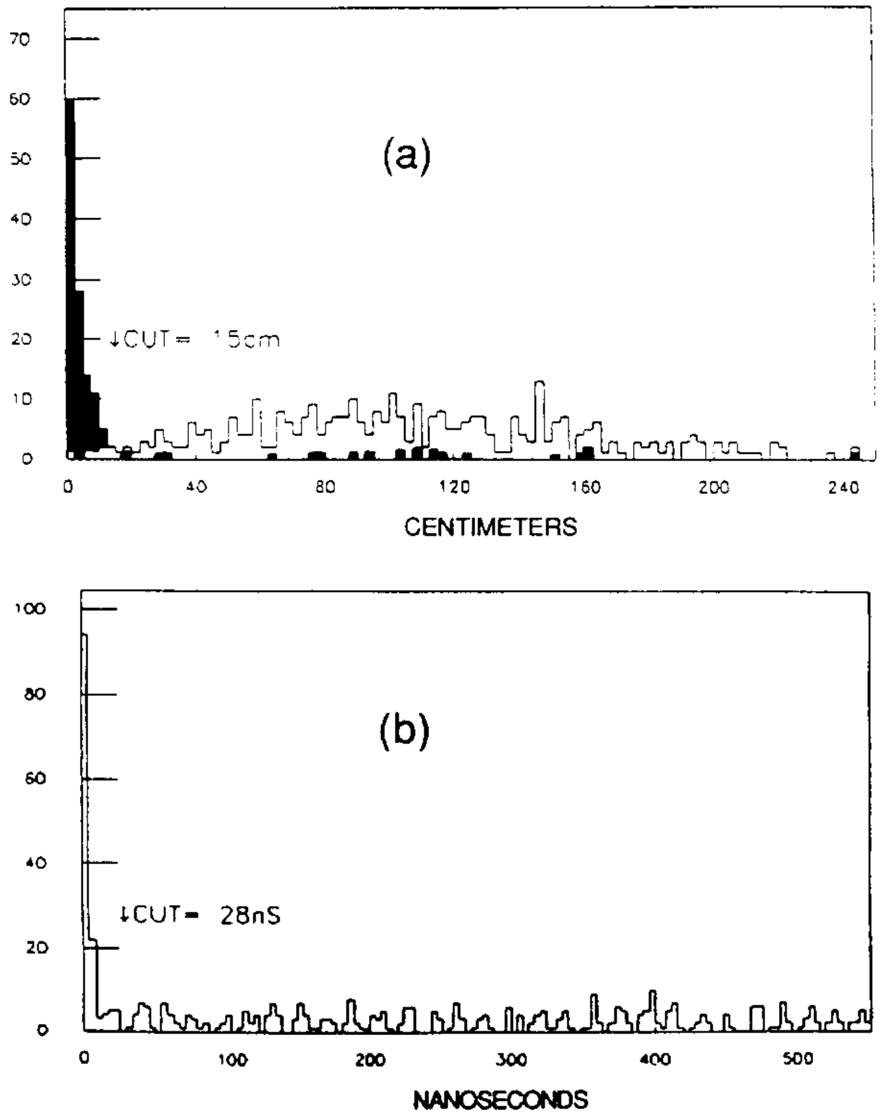


Figure 6: a) DCA of all events with δt <556 ns b) δt of events with DCA < 250 cm. In the δt plot, the data are grouped in multiples of 18.8 ns reflecting the Fermilab Tevatron r.f. structure. Shaded region in DCA represents "in time" events, unshaded region represents "out of time" events which have been **eliminated** from the data with the δt< 28 ns requirement.

Trimuons can be misidentified as a dimuon event if two of the muons pass our analysis cuts while the third muon has as momentum of less than 3.1 GeV/c. We have written a Monte Carlo to model the production of trimuon events in our detector. The radiative production of muon pairs was derived from calculations by Barger, Barnett, and Smith[8]. The momentum spectrum of hadronically produced muons was derived from π + Be $\rightarrow \mu^{+}\mu^{-}$ + X experiments[9]. The level of the hadronic muon pair production was scaled so that the sum of the two contributions matched the number of trimuons found in our detector. This predicted a misidentified trimuon background of 5.1 ν and 0.5 $\bar{\nu}$ events.

The decay of a π or K in the hadron shower accounted for 93.5 % of the same-sign dimuon background. Muons produced in the hadron shower came from two sources: 1) π/K decay of hadrons in the W-nucleon interactions (vertex contribution) and 2) π/K decay of hadrons created through the reinteraction of vertex hadrons in the calorimeter (shower contribution).

To model the vertex component, we have used the "Lepto" Lund Monte Carlo [10]. The Lund Monte Carlo parameters have been chosen to give the best agreement with fragmentation functions from BEBC[11] ν H, FNAL 15 ft. Bubble Chamber[12] ν H, and EMC[13] μH experiments. In order to investigate the A dependence of these fragmentation functions, we noted that BEBC fragmentation data indicated no difference between ν H and νNe, while EMC had reported a 7±2±3 % increase in multiplicity between carbon and copper. This multiplicity increase would correspond to a 5 % decrease in muon production in our detector. We treated the EMC result as an upper limit and included this in our vertex component uncertainty. Combining this uncertainty with systematic errors due to Lund parameter uncertainty and functional form, we have assigned an error of 12 % to the vertex component of the π/K background.

For the shower component we used the "Low-Pt" Lund Monte Carlo to generate secondary particles in our detector. The inputs to the shower Monte Carlo were the hadrons generated in the vertex component. These hadrons interacted with target calorimeter nuclei, producing daughter particles, which in turn reinteracted until all daughter particles had an energy less than 6 GeV. The particles were assigned a decay probability based on the particle's energy, lifetime, and reinteraction cross section in our iron target detector.

In the shower contribution, the target nuclear effects were important. The extrapolation from hydrogen to iron was done in two steps to minimize the systematic error. First, the "Low-Pt" Lund fragmentation functions were reweighted to agree with π- carbon data from the Serpukhov bubble chamber [14] using a propane target, and a single armed spectrometer experiment at Fermilab [15]. The extrapolation from carbon to iron was accomplished by using the weighting scheme of Busza et al[16], where the cross sections for particle production were scaled as a function of both atomic number and x_{lab}.

Finally, the resulting Monte Carlo spectrum was normalized to muon production data from our 1984 test run, in which 50, 100 and 200 GeV hadron beams interacted with our target and produced muons. The shape and level of the muon production data from hadrons in our detector agreed with the Monte Carlo to within 10 %.

From the uncertainty in this hadron shower procedure, with the addition of the vertex component which is the input to this Monte Carlo, we assigned a 15 % error to the total background from π/K decay.

Results

Table I shows the predicted backgrounds from the above-mentioned sources. The background for ν induced same-sign dimuons from conventional sources of 82.5$\pm$ 12.4 is to be compared with the observed 101 $\pm$ 10 events.

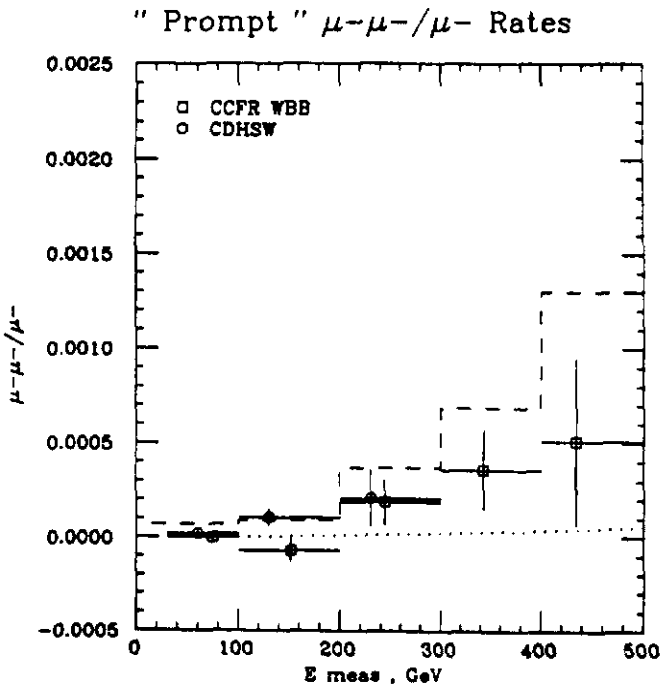
Table I: Same-Sign Dimuon Event Statistics and Predicted Backgrounds

	ν	$\bar{\nu}$
Observed Events	101 $\pm$ 10	15 $\pm$ 4
Overlays	.4 $\pm$ .2	$<$ .1
π/K decays (vertex)	50.2 $\pm$ 7.6	5.7 $\pm$ .8
π/K decays (shower)	26.8 $\pm$ 4.1	2.4 $\pm$ .4
Misidentified 3μ's	5.1 $\pm$ 2.0	0.5 $\pm$0.2
Total Background	82.5 $\pm$ 12.4	8.6 $\pm$ 1.3

Figure 7 shows the comparison of our background subtracted, acceptance corrected, same-sign results with CDHSW results, and a perturbative QCD prediction with $m_c = 1.25$ GeV/c^2. Our 75 Gev and 230 GeV points are in good agreement with CDHWS while our 150 GeV point is two standard deviations lower. All of our data points are with within 1.5 σ of the QCD gluon bremsstrahlung prediction.

To further demonstrate the similarity between the ν induced same-sign data and the conventional background Monte Carlo, we show two kinematical distributions for the second muon (Figure 8). There is good agreement in both shape and normalization between the Monte Carlo and the data. There is no indication of anomalous behaviour.

Figure 7: Comparison of the most recent CCFR and CDHSW measurements of prompt same-sign dimuon production for $P_\mu > 9$ GeV/c. The dashed line is the CCFR 90% confidence level upper limit. The dotted curve is a first order QCD gluon bremsstrahlung calculation from ref. [5] with $m_c = 1.25$ GeV/c^2.



Conclusions

We observe 101 ν induced same-sign dimuons with energies between 30 GeV and 600 GeV. A detailed calculation of the backgrounds from conventional sources gives a background of 82 $\pm$ 12 events yielding a "prompt" signal of 18.5 $\pm$ 15.9 events. The rate for prompt same-sign dimuon production is .24 $\pm$ .43 $\times 10^{-4}$ (.92 $\times 10^{-4}$ 90 % c.l. upper limit) for E_ν 30-300 GeV, and 3.40 $\pm$ 1.96 $\times 10^{-4}$ (6.38 $\times 10^{-4}$ 90 % c.l. upper limit) for E_ν 300-600 GeV. The rate for prompt same-sign dimuon production between E_ν 30-600 GeV is .55 $\pm$ .47 $\times 10^{-4}$ (1.26 $\times 10^{-4}$ 90 % c.l. upper limit).

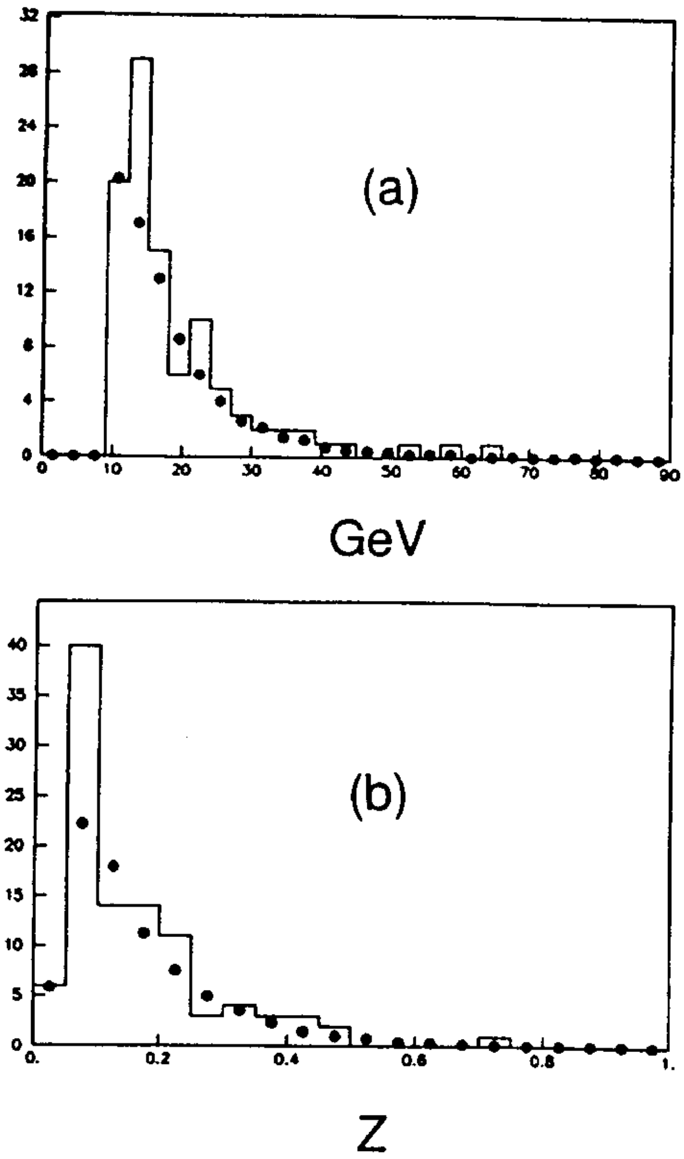


Figure 8: a) The momentum distribution of the second muon b) The fraction z of the total hadron shower energy $E_{had} = E_{\mu_2} + E_{cal}$ carried by the second muon. The dots represent the background Monte Carlo prediction. Each distribution is consistent with conventional background.

A comparison of our same-sign dimuon data for $E_\nu < 300$ GeV with those obtained by CDHSW shows that they are in good agreement, with the CCFR rates being slightly lower (especially the 150 GeV E_ν data point). In both the low energy data and previously unmeasured high energy data, the rates and kinematic distributions give no compelling evidence for anomalous same-sign dimuon production.

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