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A Lower Bound on the Intermediate Boson Mass*

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ABSTRACT

We report a search for the W-boson via the production process $\nu_\mu + Z \rightarrow W^+ + \mu^- + Z$ and decay process $W^+ \rightarrow \mu^+ + \nu_\mu$. We have set a firm lower bound on the mass of the W-boson as a function of the branching fraction into leptons ($B = \frac{W \rightarrow \ell + \nu}{W \rightarrow \text{all}}$). For example, we have determined that $M_W > 4.6$ GeV/c^2 (90% confidence limit) for B = 0.5.

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It is well known that the ordinary four-fermion theory of the weak interaction predicts incorrect behavior at high energies. In particular, it is easily shown that the theory predicts a total neutrino cross section on point-like particles that grows linearly with laboratory energy ($\sigma_{Fermi} \propto G^2 E_{lab}$). This rising cross section eventually violates the s-wave unitarity bound at $E_{lab} \sim 10^5$ GeV.

One possible modification to this weak interaction theory is to introduce an intermediate spin 1 particle, the W-boson, which mediates the interaction.[1] Its propagator term $G \rightarrow G/(1 + q^2/M_W^2)$ serves to damp the cross section at large q^2 (four-momentum transfers). This retains the correct low energy behavior, but now yields a total neutrino cross section that asymptotically grows logarithmically ($\sigma \propto \ln \frac{2M_p E_{lab}}{M_W^2}$). This does not completely solve the theoretical difficulties, and more than just the addition of a single spin 1 boson is needed to obtain a finite theory of the weak interaction.

Estimates of the W-boson mass are model dependent and vary widely. For example, the cutoff energies calculated from second order processes like the K_L-K_S mass difference and the $K_L \rightarrow \mu^+ + \mu^-$ rate are 3-15 GeV,[2] while theories that unify the weak and electromagnetic interactions yield $M_W \sim 37$ GeV.[3]

Experimentally, W-bosons could be produced by hadrons, muons, or neutrinos. At present, there is no positive evidence for the existence of W-bosons, although there have been several searches.

In hadron collisions, the process

$$p + Z \rightarrow W^{\pm} + \text{hadrons}$$
$$\hookrightarrow \mu^{\pm} + \nu$$

was searched for at the Brookhaven A. G. S.[4] An upper limit $\sigma_W B' \leq 6.10^{-36}$ cm^2 for M_W between 2.0 and 4.5 GeV/c^2 was obtained for this process ($B' = W \rightarrow \mu\nu / W \rightarrow \text{all}$). However, uncertainties in the branching ratio and production cross section for W-bosons make it difficult to conclude that a firm lower bound was set.

Experiments attempting to directly produce W-bosons with neutrino beams have been carried out both at Brookhaven and CERN.[5] The production process,

$$\nu_\mu + Z \rightarrow W^+ + \mu^- + Z$$

with decay modes

$$W^+ \rightarrow \begin{cases} \mu^+ + \nu_\mu \\ e^+ + \nu_e \end{cases}$$

$$\rightarrow \text{hadrons}$$

has been searched for. In this case, production cross sections and distributions of the final products can be reliably calculated. The W-boson decays promptly ($\Gamma > 10^{18}$ sec^{-1}), but there is no reliable estimate of the leptonic to hadronic branching ratio.

Neutrino experiments looking for all three decay modes have been carried

out, and firm lower limits of $M_W \gtrsim 2$ GeV/c^2 have been set.[5]

We report here the initial results from a new neutrino experiment using much higher energy neutrinos. The experiment, which uses counter-spark chamber techniuqes, is set up at the National Accelerator Laboratory (NAL), Batavia, Illinois. As a first task, we have searched for directly produced W-bosons which decay by the mode $W^+ \rightarrow \mu^+ + \nu_\mu$. Our experiment differs from previous experiments in that we use a dichromatic rather than a broad-band neutrino beam.

The most important neutrinos for W-production have high energy, but a broad-band spectrum is strongly peaked toward low energies. The narrow band beam has little low-energy neutrino and anti-neutrino background. This eliminates a potentially serious problem when searching for events where most of the final-state energy cannot be observed or where positively charged leptons are expected to be produced. Both of these are true in W production: The μ^+ from W decay is one of the unique signatures of the event, and the final-state neutrino typically carries away over half of the energy. Thus, the narrow band beam combined with the high energies available at NAL, gives us a considerable advantage over previous neutrino experiments.

To produce the neutrino beam, the primary 300 GeV NAL proton beam was targeted in the Neutrino Hall, 975 meters upstream of our detection apparatus. The secondary hadrons were momentum-selected at 160 GeV with a momentum bite of ± 11%, focused into a parallel beam, and directed into a 345 meter decay tunnel followed by 530 meters of earth and iron shielding.

The neutrinos were produced through the decays $\pi \rightarrow \mu\nu$ and $K \rightarrow \mu\nu$. Since this is a two-body decay, the energy of the neutrino was determined by its angle in the lab, with the highest detected energies in the forward direction and the lowest at the largest angle subtended by our apparatus. For the 160 GeV hadron beam, the mean neutrino energies for K-decay are 145 GeV, and for π-decay are 50 GeV.

A schematic of our apparatus is shown in Fig. 1. The relevant information for analyzing an event is the muon momentum and angle determined by the spark chambers and magnet, and the total hadron energy measured by the calorimetry counters in the target. Summing the muon and hadron energies gives a first estimate of the incident neutrino energy, sufficient to separate π and K-decay neutrinos. Time-of-flight measurements and fiducial cuts on the interaction point serve to eliminate cosmic rays and machine-associated muons which penetrate the shield. These are the only potential background sources for neutrino events in the experiment.

The principle neutrino interaction which occurs is

$$\nu + N \rightarrow \mu^- + \text{hadrons} ,$$

which is the weak interaction analog of electromagnetic deep-inelastic electron scattering. If a W exists, the analogy is particularly close since the W^+ replaces the photon as the mediator of the interaction. Scaling behavior at the hadron vertex, demonstrated to exist in e-p scattering,[6] is also expected here. This, in fact, has been observed in the lower-energy CERN

experiments, which show that to a good approximation $2x\,F_1(x) = F_2(x)$ and $-x\,F_3(x) = F_2(x)$, where the scaling variable is $x = -q^2/2M_p\nu$.[7] Here $F_2(x) = \frac{9}{5} F_2^{eN}(x)$, where $F_2^{eN}(x)$ is the structure function measured in e-d inelastic scattering.[8] These are the same scaling functions one obtains from scattering off spin ½ partons with V-A coupling and no anti-parton contributions. We have used these in the discussion of μ^- production below, but our results are quite insensitive to assumptions about the relative sizes of F_1, F_2, and F_3.

If a low-mass W exists, it will manifest itself in two ways: by being directly produced through $\nu N \to \mu^- W^+ N$ (Fig. 2b), and by reducing the total cross section through its propagator (Fig. 2a). We have combined both of these effects by looking at the ratio of W-production to ordinary neutrino events, using the structure function assumptions stated above.[8]

The data reported in this paper were taken in January 1973, during a run of 2.7 10^{16} protons on target. The secondary hadron beam was set to focus positive 160 GeV particles. The decays from this beam yielded two bands of neutrinos as described above.

As a result of this run, 167 neutrino interactions have been identified This is a clean sample, since background problems are negligible. In order to facilitate the analysis, we have applied geometric fiducial cuts to the data. This reduced our data sample to 145 events. Also, events that could not be completely reconstructed have been eliminated, further reducing our sample to 112 "analyzable" events. The second class of events eliminated were all identifiable as ordinary neutrino interactions ($\nu_\mu + N \to \mu^- +$ hadrons)

Recall that for W-production, we expect a low energy μ^- produced along with the W-boson, and a higher energy μ^+ from W-decay. In our apparatus, we then expect to observe and identify a pair of muons. Typically, only the μ^+ is energetic enough to traverse our toroidal magnet and be sign selected.

Analyzing our sample of 112 events, we find no events with a pair of muons. In order to simplify the criteria, we have also searched our data for "wrong sign" muons. We find that only 1 out of 112 events has a μ^+, rather than a μ^-. In other words, asking the simplest possible requirement (the presence of a positive muon) gives only one potential W-candidate. A detailed examination of this event shows visible hadron energy deposition in the calorimeter and no evidence for an accompanying μ^-. This event appears to be due to an independently observed anti-neutrino contamination.

We conclude that there is no evidence for W-bosons in our experiment. We are confident in this conclusion, since we could identify the events as not being W-bosons so easily.

In order to determine our sensitivity, we have calculated the event rates for $\nu + N \rightarrow \mu^- +$ hadrons and $\nu + Z \rightarrow \mu^- + W^+ + Z$ with $W^+ \rightarrow \mu^+ + \nu$ in a Monte Carlo calculation which assumes the following: (1) the scaling functions described above; (2) the effects of a W-propagator; (3) calculated W-production cross sections[9]; and the calculated decay distribution for $W^+ \rightarrow \mu^+\nu$. Figures 2c shows the expected fraction of detected W-events in our apparatus as a function of E_ν and M_W.

In our sample of 112 events, there are 18 kaon neutrino and 94 pion neutrino interactions. From the energy spectrum of these observed 112 neutrino interactions, we have estimated the expected number of $W \rightarrow \mu^+\nu$ events for our apparatus. This is given for various mass W-bosons in Table I. Our 90% confidence bound as a function of the branching fraction is shown on Fig. 3. For comparison, the previous CERN neutrino limit is also shown.

In conclusion, we see no evidence for W-bosons in this experiment. A lower bound has been set on the mass (i.e., $M_W > 4.6$ GeV/c^2 for B = 0.5) which depends on the branching fraction into leptons. This limit represents a significant improvement over past neutrino results.

We would like to especially acknowledge J. Smith for helpful discussions about W-production cross sections and use of his computer programs. Les Oleksiuk was of great assistance in the early stages of the experiment. We also appreciate the help and support of the NAL staff, especially members of the Neutrino Laboratory.

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   It is important to note that if these assumptions break down in such a way as to reduce μ^- production (as would happen if partons showed non point-like behavior) then our mass limit would be higher than we state.
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Table Caption

The number of expected $W \rightarrow \mu^+\nu$ events expected in our experiment. This has been estimated using the energy spectrum of the sample of 112 ordinary ν-events and the information from Fig. 1c. These rates are given for B = 1 and should be scaled accordingly.

Figure Captions

Figure 1: The neutrino target-detector consists of 80 liquid scintillator counters, each separated by 4" of steel. Every fourth counter is followed by a spark chamber with magnetostrictive readout. A muon spectrometer, consisting of an iron-core toroidal magnet and four more spark chambers follows the 170 ton target-detector.

Figure 2: (a) Deep inelastic neutrino scattering, mediated by the hypothetical W.

(b) W^+ production (a similar diagram with W - N interaction has been omitted).

(c) The predicted ratio of observed events of type (b) to type (a) as a function of neutrino energy and W mass. The detection efficiency of the apparatus, the W^+ production cross section, and the μ^- production cross section with W-propagator are all included.

Figure 3: The upper curve is the lower limit (90% CL) on W mass set by this experiment and presented as a function of the decay branching ratio of the W^+ into leptons. Previous limits are also shown.

TABLE I

$M_W(GeV/c^2)$	Expected Number of W-events
3.0	42.
4.0	8.4
5.0	2.1
6.0	.8

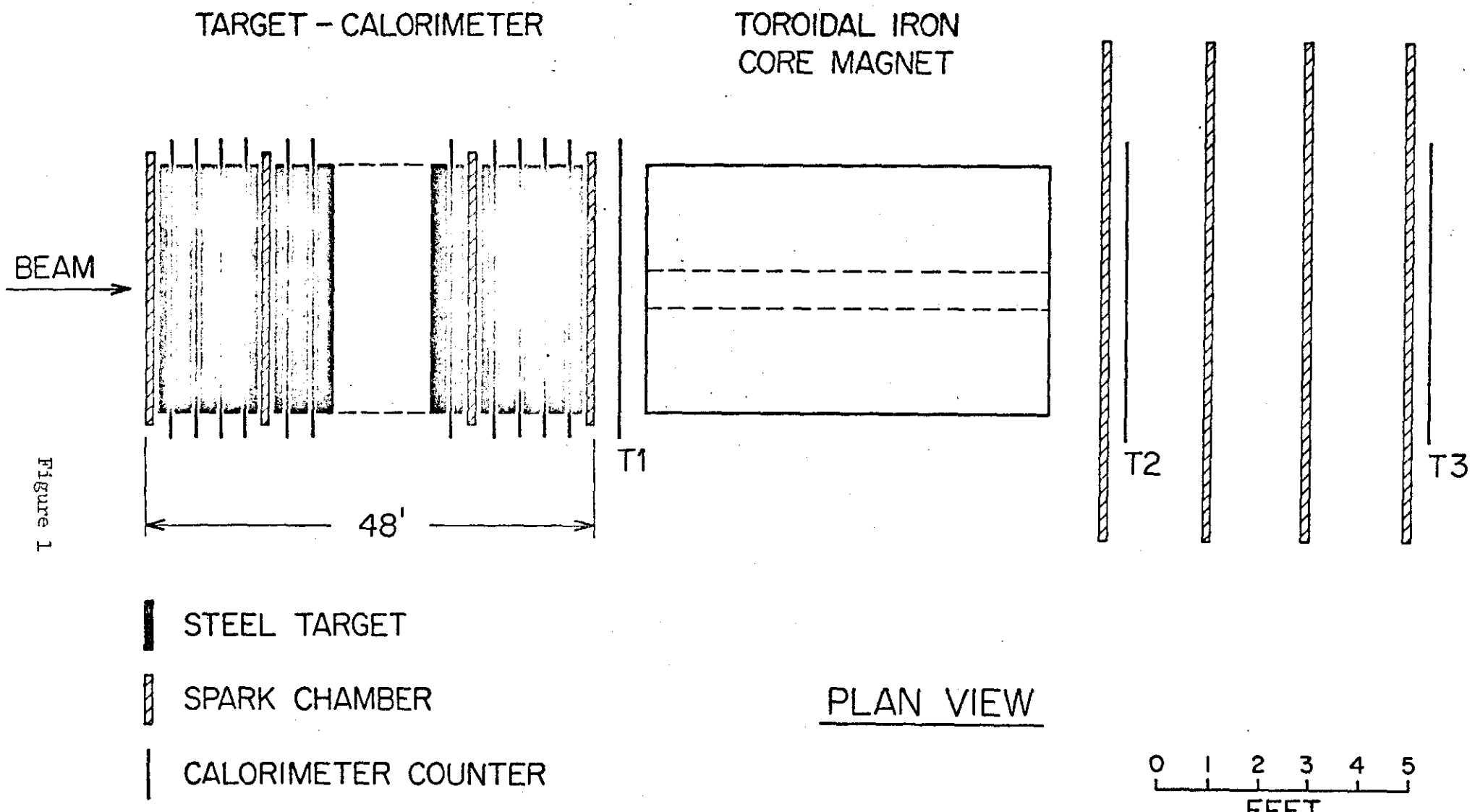
TARGET - CALORIMETER
TOROIDAL IRON
CORE MAGNET
BEAM
T1
T2
T3
48'
STEEL TARGET
SPARK CHAMBER
CALORIMETER COUNTER
PLAN VIEW
0 1 2 3 4 5
FEET

Figure 1

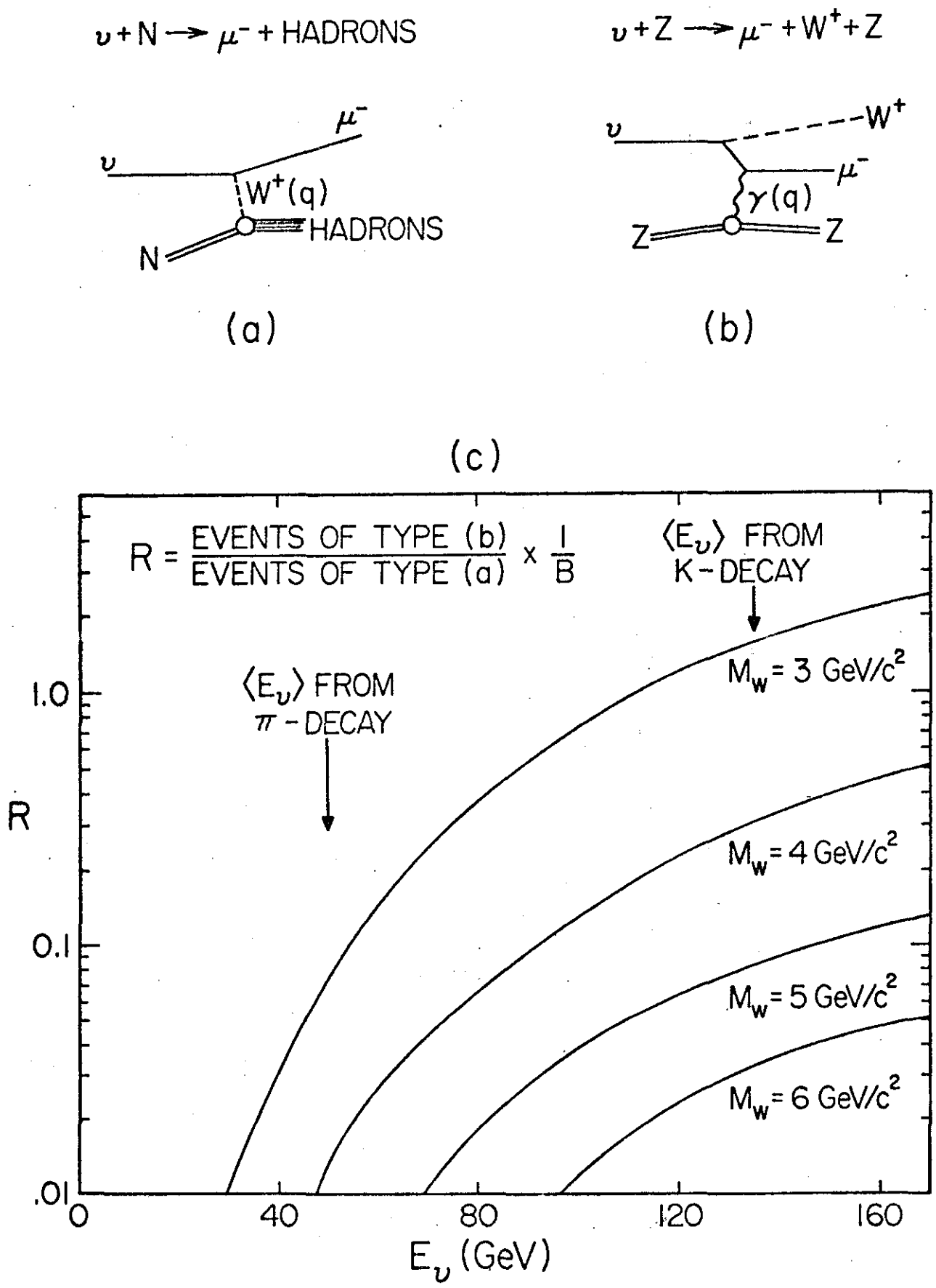
$\nu + N \rightarrow \mu^- + \text{HADRONS}$
$\nu + Z \rightarrow \mu^- + W^+ + Z$
μ^-
ν
$W^+(q)$
HADRONS
N
(a)
ν
W^+
μ^-
$\gamma(q)$
Z
Z
(b)
(c)
$R = \frac{\text{EVENTS OF TYPE (b)}}{\text{EVENTS OF TYPE (a)}} \times \frac{1}{B}$
$\langle E_\nu \rangle$ FROM K-DECAY
$\langle E_\nu \rangle$ FROM π-DECAY
$M_W = 3$ GeV/c^2
$M_W = 4$ GeV/c^2
$M_W = 5$ GeV/c^2
$M_W = 6$ GeV/c^2
R
1.0
0.1
.01
0
40
80
120
160
E_ν (GeV)

Figure 2

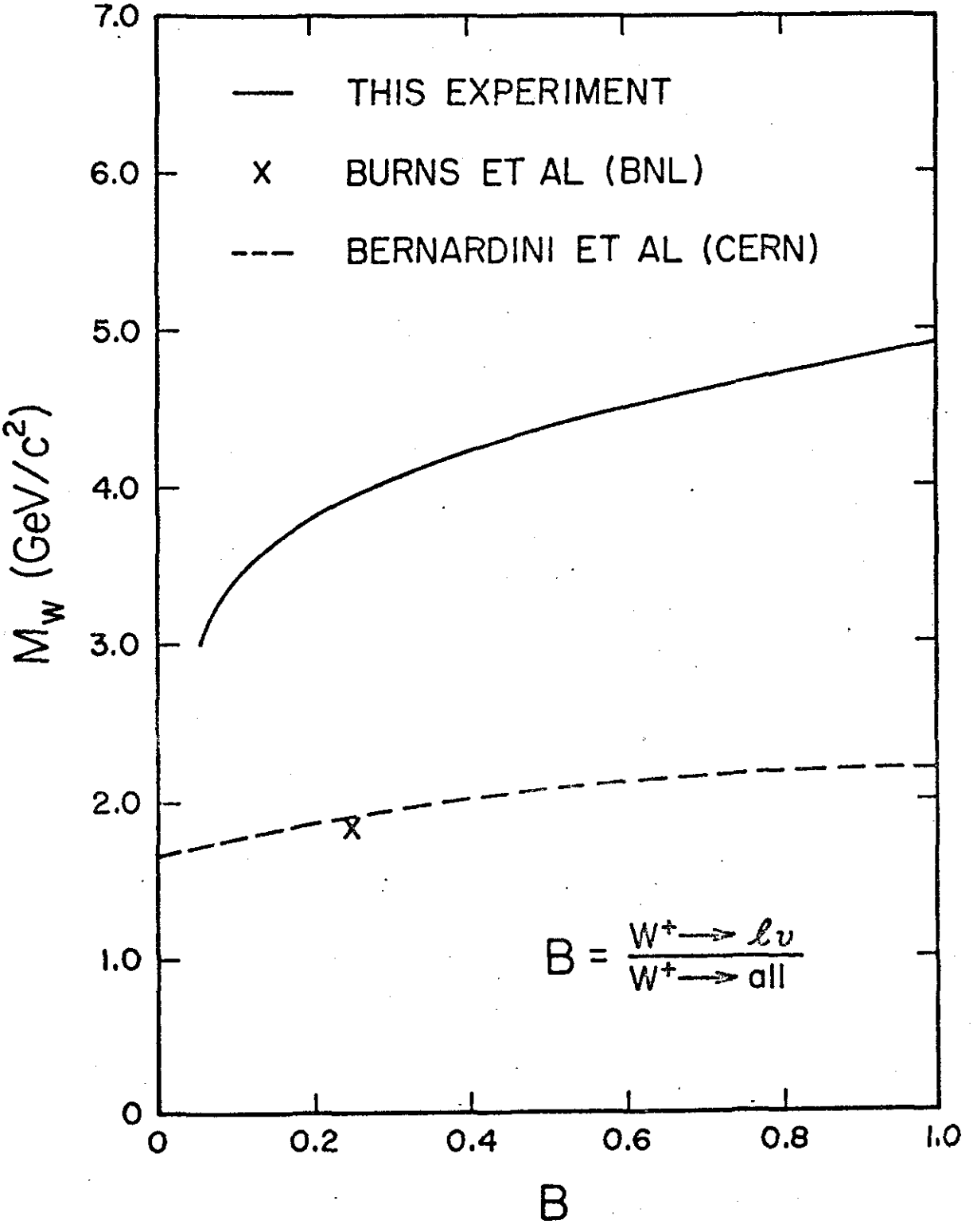
THIS EXPERIMENT
BURNS ET AL (BNL)
BERNARDINI ET AL (CERN)
M_W (GeV/c^2)
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
0
0.2
0.4
0.6
0.8
1.0
B
$B = \frac{W^+ \to \ell \nu}{W^+ \to \text{all}}$

Figure 3