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GAUGE-THEORY HEAVY MUØNS: AN EXPERIMENTAL SEARCH*

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Abstract

The result of a sensitive search for positively charged heavy leptons coupled to the muon neutrino is reported. In a beam consisting largely of neutrinos, 1522 events with a μ^- secondary and 8 events with a μ^+ secondary were found. These latter events are consistent in number and kinematic properties to those expected from beam contamination by $\bar{\nu}_\mu$. This experiment, therefore, sees no evidence for production of such heavy leptons. Assuming a coupling constant equal to the universal Fermi constant and branching ratio to muons B = 0.3, our 90% confidence lower limit corresponds to $M_{Y^+} \gtrsim 8.4$ GeV/c^2.

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Recently, several experiments[1] have been conducted to search for new members of the lepton families. Thus far, no evidence has been found for their existence up to masses of about 2.5 GeV/c^2. However, there are theoretical reasons to pursue the question of whether such positively charged heavy muons exist, since they may help provide[2] the mechanism for non-divergent behavior of the weak interactions at high energies. In some gauge models using heavy muons and electrons, calculations[3] indicate that the positively charged heavy muon must be less massive than about 7 GeV/c^2, in order to be consistent with present experimental measurements of the muon magnetic moment. We report here the conclusions of an experiment in the mass range up to about 8 GeV/c^2.

The experiment was performed in the narrow-band neutrino beam at NAL during July and August 1973. Extracted protons of energy 300 GeV bombarded the production target. The secondary hadron beam was set to transmit positive hadrons with average energy of 165 GeV, and $\Delta p/p \approx 0.35$. The π^+ and K^+ decays in the 345 m decay pipe provide a spectrum of neutrinos with two peaks at $E_\nu \approx 50$ GeV and $E_\nu \approx 135$ GeV, respectively. We also expect, at much smaller energies ($E_\nu \lesssim 25$ GeV) a contamination of neutrinos and anti-neutrinos from pion and kaon decays occurring in the region immediately downstream of the production target, prior to momentum and sign selection. Because the beam is sign selected, all negative hadrons are removed before the decay pipe region. The anti-neutrinos from this source form the major background in this experiment.

The neutrino detection apparatus,[4] located 500 m from the end of the hadron decay region, consists of 160 tons of iron interspersed with scintillation

counters and spark chambers, followed by an iron-core toroidal magnet and additional spark chambers. The target is 576" long and 60" x 60" in cross-section. Both final state energies from the reaction

$$\nu_\mu + N \rightarrow \mu^- + \text{hadrons} \tag{1}$$

are determined with this apparatus: the muon energy is measured by observation of the bend angle in the iron-core magnet, and the hadron energy is measured by calorimetry using the scintillation counters located inside the steel target. The apparatus was triggered whenever a particle traversed trigger-counters located on both sides of the spectrometer magnet, or when more than 10 GeV in hadron energy was dissipated in the calorimeter.

combined trigger

Positively charged heavy muons (Y^+) would be produced[5] by a reaction analogous to reaction (1):

$$\nu_\mu + N \rightarrow Y^+ + \text{hadrons} \tag{2}$$

The heavy lepton would subsequently decay in the mode

$$Y^+ \rightarrow \mu^+ + \nu_\mu + \nu_\mu \tag{3}$$

with a calculable rate $\Gamma(\mu^+) \gtrsim 10^{13}$ sec $^{-1}$, and a branching ratio $B = \Gamma(\mu^+)/\Gamma(\text{all})$. This ratio will lie within the limits $0 < B < 0.67$, depending on the other possible modes of decay. The most likely decay mode to compete with reaction (3), would be $Y^+ \rightarrow \nu_\mu + \text{hadrons}$. Current algebra relates[5] B to the asymptotic ratio, $K = \sigma(e^+ e^- \rightarrow \text{hadrons}) / \sigma(e^+ e^- \rightarrow \mu^+ \mu^-)$. For $K = 2$, the "colored quark model", the result is that $B \approx 0.3$ for $M_Y \gtrsim 2$ GeV/c^2.

For this heavy muon search, the spectrometer polarity was set to focus positives, and hence maximize the acceptance. Events with a single final-state muon traversing the spectrometer magnet were selected from the triggered sample. In order to guarantee neutrino production, it was further required that the production vertex was located well inside the target: at least three inches from

the transverse edges of the steel, forty inches from the upstream end, and 126 inches from the downstream end. There were 1530 events satisfying these conditions. Eight of these events had a positive muon in the final state; the rest were negatively charged. Figure 1 shows the distribution in the total observed energy for the latter 1522 events. This shows the characteristic two peak spectrum expected from the pion and kaon neutrinos.

The primary signature of heavy muon production is the observation of positively charged muons created from a beam consisting of neutrinos with little contamination from antineutrinos. Such "wrong-sign muons" can arise from the following sources: (a) production by background anti-neutrinos ($\bar{\nu}_\mu + N \rightarrow \mu^+ +$ hadrons); (b) incorrect determination of the muon charge with the spectrometer magnet; (c) production and decay of heavy muons by reactions (2) and (3); (d) production and decay of charged intermediate vector bosons; (e) some other "exotic" mechanism, such as violation of the conservation of muon number. The production and decay of charged bosons (d) would provide additional signatures and a report on the search for such anamolous effects will be the subject of a future paper.

Processes (a) and (b) form the sole backgrounds for this experiment. We estimate that we expect to misidentify less than 0.9 events out of 1522 right-sign events due to resolution and large-angle scattering in the magnet (b). In order to calculate the number of wrong-sign events from anti-neutrinos (a), we have determined our energy-dependent acceptance in a Monte-Carlo calculation, which assumed the usual quark model structure functions. This calculation reproduced the general features of the observed distributions in neutrino interaction vertex, muon position at several counters and the magnet, and in the scaling variables (x,y) shown by the 1522 accepted μ^- events.

The relative number of background $\bar{\nu}$ was calculated, with the normalization constrained by preliminary analysis of hadron fluxes in this beam. We estimate these fluxes are known to within a factor of two. We calculate an expected level of (10.2 ± 5.1) observed μ^+ events from this source. As a check on this estimate, we ran

for some period with a primarily anti-neutrino beam. Under those circumstances the wrong-sign muons are μ^- from ν interactions, and form a relatively larger fraction of the total observed events. This is due to the larger production of π^+, K^+ relative to π^-, K^- and the larger cross-section for ν relative to $\bar{\nu}$. We estimate (6.1 ± 3.0) ν background events for this case, relative to 60 observed $\bar{\nu}$ events with a μ^+ in the final state. There were six wrong-sign events observed, in good agreement. We conclude that (11.1 ± 5.1) wrong-sign events with a final-state μ^+ are to be expected from background sources (a) and (b) in the ν sample. The observed eight events are consistent with this estimate. It should be noted that even if the observed wrong-sign muons were all to represent signal, the decaying heavy muon would have to be of order 8 GeV/c^2 in mass, for usual assumption of branching ratio and coupling.

Even though the number of observed μ^+ is consistent with background estimates, it is interesting to examine the character of these events. We have attempted to exploit the kinematic differences between heavy muon production (c) and background, primarily process (a). There are two major differences to be expected.

(1) Production and acceptance of heavy muons, especially at large mass, are dominated by the highest energy kaon neutrinos, typically $\langle E_\nu \rangle \simeq 150$ GeV. About half this energy goes into the final state hadrons of reaction (2), and some fraction of the remainder goes into the final μ^+ of the decay (3). The total observed energy $E_{meas} = E_{had} + E_\mu^+$, is expected to be of order $\langle E_{meas} \rangle \simeq 80$ GeV. Production of μ^+ by $\bar{\nu}$, on the other hand, should reflect a steeply-falling flux curve characteristic of background $\bar{\nu}$, and would peak at considerably lower energy. Figure (2a) shows the expected distributions in $E_{meas} = E_\mu + E_{hadron}$ for events observed under these two assumptions with the data histogram superimposed. The data are consistent with the expected background, and much less consistent with production and decay of high mass leptons.

(2) The distribution in the observed inelasticity $y_{meas} = E_{had}/E_{meas}$ is expected to be substantially different for Y^+ decay and $\bar{\nu}$ production.[1] The loss of energy through the final state neutrinos of Y^+ decay results in a relatively large fraction of the total visible energy in the hadrons at the production vertex. From $\bar{\nu}$ production, on the other hand, the hadrons tend to have only about 25% of the incident neutrino energy. Figure (2b) shows the y_{meas} distributions to be expected for the two mechanisms, with the histogram of the data superimposed. The data lie at small values, more consistent with background than with production of heavy leptons.

We conclude that the observed wrong-sign events are consistent with expected backgrounds, both in absolute numbers and in internal distributions. The data is inconsistent with a range of heavy lepton masses, depending on assumptions of branching ratio and coupling constant.

The sensitivity of the search for heavy leptons as a function of its mass, was obtained from the same Monte-Carlo calculation discussed previously. In this calculation the differential and total cross-sections for process (2) were determined by quark model predictions.[5] This is expected to be a lower limit on the production of such particles. The polarization of the Y^+ was calculated for each event,[6] and the subsequent decay distribution in accordance with usual V-A assumptions.[7] This Monte-Carlo program was also used to obtain the theoretical curves for y_{meas} and E_{meas} discussed previously.

In order to eliminate the need for reliance on normalized background calculations in setting a limit on heavy muon production, we have chosen to apply a cut to both the data and the Monte Carlo calculation. For the requirement $y_{meas} > 0.5$, all μ^+ events are removed from the data sample (see figure 3b), while the expected background μ^+ is reduced to < 0.6 events. The number of events expected from heavy lepton decay is reduced by roughly a factor of two, independent of Y^+ mass, with this cut.

Figure (3) shows the resulting 90% confidence limit as a function of heavy lepton mass and the product $B\, G_Y^2 / G_F^2$. If we assume, for example,[5] $B = 0.3$ and $G_Y = G_F$, we find $M_Y > 8.4$ GeV/c^2. The theoretical estimate of the branching ratio, B, depends on usual current algebra assumptions and the asymptotic ratio $(s \to \infty) : K = \sigma\ (e^+ e^- \to \text{hadrons}) / \sigma\ (e^+ e^- \to \mu^+ \mu^-)$. The colored quark assumption, $K = 2$, gives $M_Y > 8.4$ GeV/c^2 with $G_Y = G_F$. Experimentally, values as high as $K = 6$ have been measured.[8] Our limit on the heavy muon mass is somewhat insensitive to the actual asymptotic limit. Even for $K = 10$, $B = .12$ is expected, and the limit is $M_Y > 7.2$ GeV/c^2. We conclude that unless some pathological anomaly provides enormous coupling to hadrons for 7 GeV/c^2 heavy muons, their existence with equal coupling ($G_Y = G_F$) is unlikely.

For lower masses, the hadronic decay rate calculations are less dependent on extrapolation. In this case, the limit of figure (2b) represents a limit on the relative couplings of a heavy lepton. For example, at $M_Y = 1$ GeV/c^2, we expect $B = 0.3$ and find $|G_Y|^2 < .02\, |G_F|^2$.

In conclusion, we see no evidence for a charged positive heavy muon (lepton number = +1) coupled to muon neutrinos. It now appears, in contrast to very simple gauge models, that if such a heavy lepton exists it is either very massive or has a small effective coupling constant.

Footnotes

1. B. Barish, et.al., Phys. Rev. Lett. 31, 180 (1973); Deden, et.al., Phys. Lett. 46B, (1973); Bologna, Cern, Frascati collaboration, summary talk by G. Salvini, Proceedings of XVI International Conference on High Energy Physics at NAL, Vol. II.
2. H. Georgi and S. L. Glashow, Phys. Rev. Lett. 28, 1494 (1972).
3. J. Primack and H. Quinn, Phys. Rev. D6, 3171 (1972); K. Fujikawa, et.al., Phys. Rev. D6, 2923 (1973); J. Primack, Proceedings of XVI International Conference on High Energy Physics at NAL, Vol. II.
4. B. Barish, et.al., Phys. Rev. Lett. 31, 565 (1973).
5. J. D. Bjorken and C. H. Llewellyn-Smith, Phys. Rev. D7 887 (1973); C. H. Llewellyn-Smith, Cern Report No. CERN-Th-1621, 1973 (unpublished).
6. Private communication, J. Smith (SUNY, Long Island, N.Y.); A. Soni, Columbia Report CO-2271-23, 1973 (unpublished).
7. Heavy leptons produced by neutrinos would have predominantly negative helicity. The μ^+ from a V-A decay interaction have smaller laboratory acceptance than from V+A decay. For example, if $M_Y = 8$ GeV/c^2, the V+A decay assumption would produce a factor of 1.25 increase in the expected number of detected μ^+.
8. Preliminary result reported by B. Richter, Conference on Lepton Induced Reactions, Irvine, California, Dec. 1973 (unpublished).

Figure Captions

1. Distribution in total measured energy (GeV) for 1522 observed events with negative muon secondary.

2. (a) Distribution in total observed energy, E_{meas}, in GeV for $8\mu^+$ events and (b) distribution in observed inelasticity, y_{meas}. The data are shown as histograms. Expected distributions for wide band background (WB) from $\bar{\nu}$ interactions and 8 GeV/c^2 heavy lepton production (HL) are shown as solid curves.

3. 90% confidence limit on heavy lepton mass versus $B(G_Y/G_F)^2$. The theoretical branching ratio, B, is also shown for two assumptions for the asymptotic value of the ratio, $K = \sigma\ (e^+e^- \rightarrow \text{hadrons})/\sigma\ (e^+e^- \rightarrow \mu^+\mu^-)$.

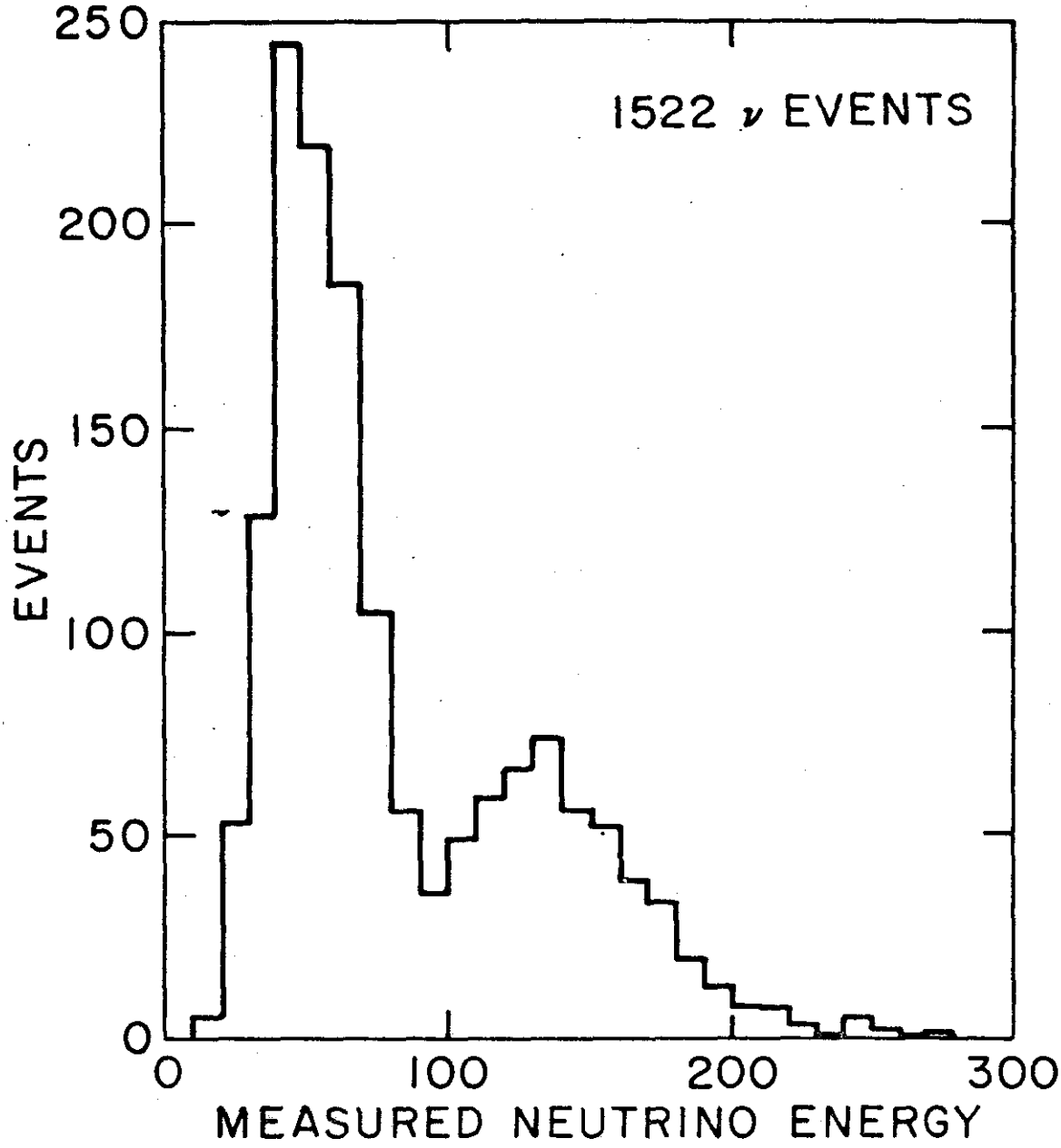
1522 ν EVENTS
EVENTS
250
200
150
100
50
0
0
100
200
300
MEASURED NEUTRINO ENERGY

Fig. 1

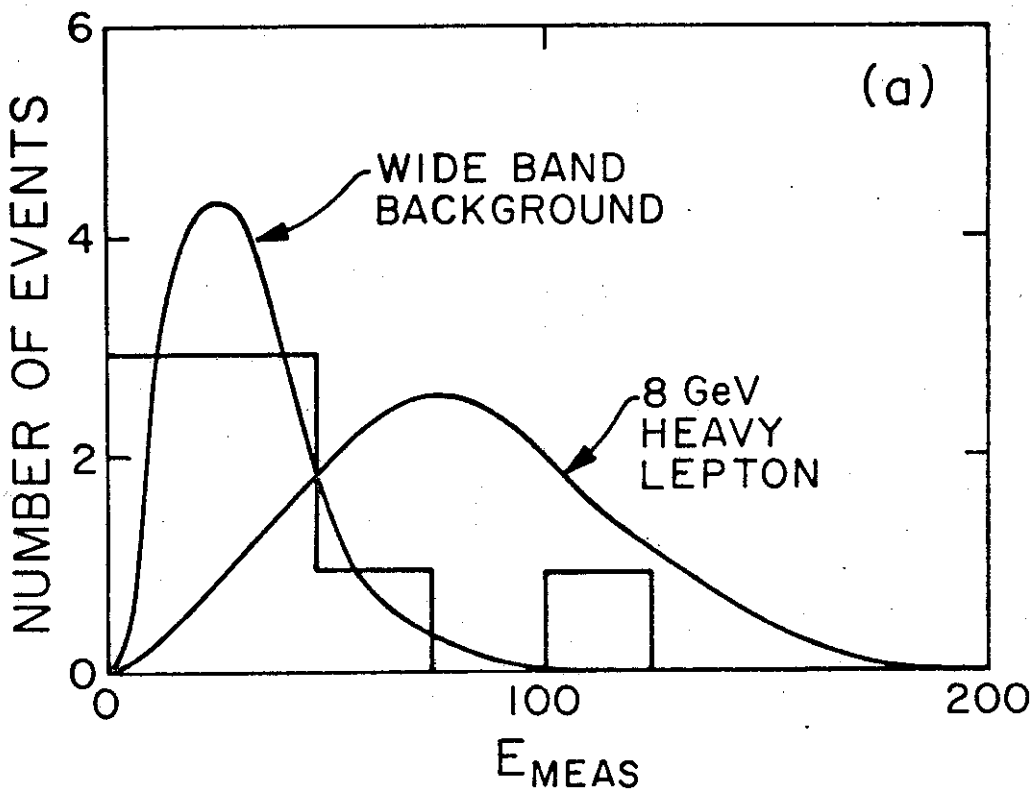
(a)
WIDE BAND
BACKGROUND
8 GeV
HEAVY
LEPTON
NUMBER OF EVENTS
0
2
4
6
0
100
200
E_{MEAS}

Fig. 2a

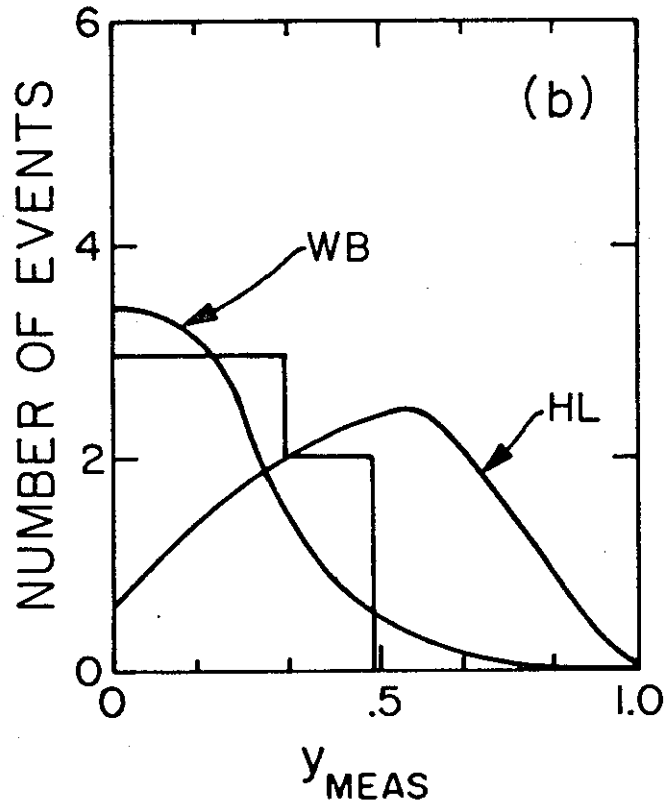
(b)
WB
HL
NUMBER OF EVENTS
0
2
4
6
0
.5
1.0
y_{MEAS}

Fig. 2b

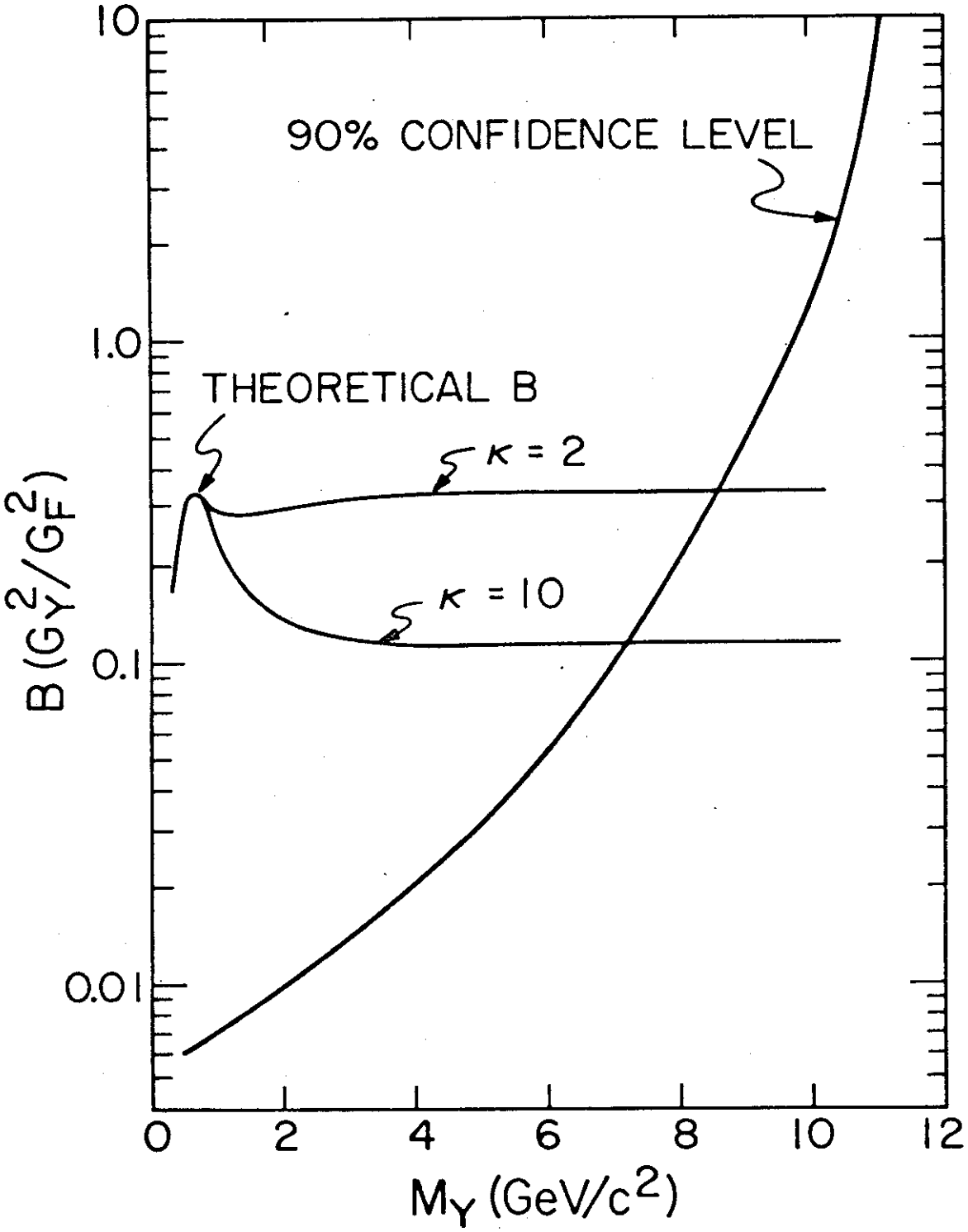
10
1.0
0.1
0.01
90% CONFIDENCE LEVEL
THEORETICAL B
κ = 2
κ = 10
B (G_Y^2/G_F^2)
0
2
4
6
8
10
12
M_Y (GeV/c^2)

Fig. 3